Jet Energy Calibration

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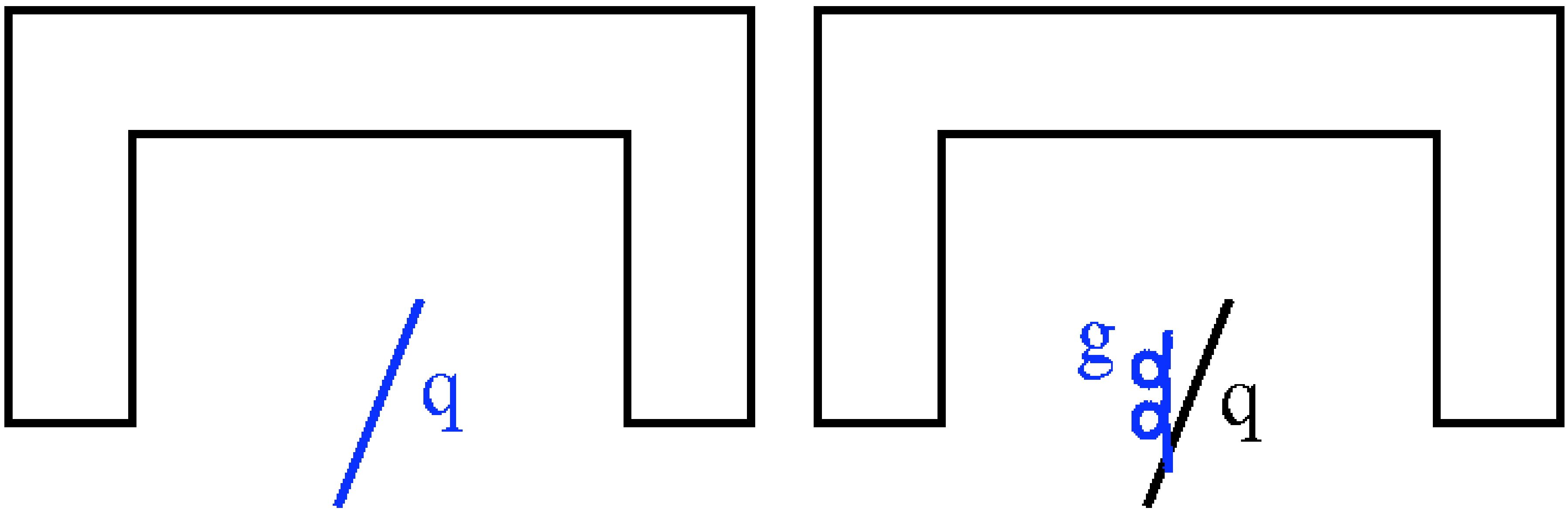
Outline

- Introduction
- CDF and D0 calorimeters
- Response corrections
- Multiple interactions
- η-dependent corrections
- Underlying event and Out-of-cone energy
- Other calibration signals
- Conclusions

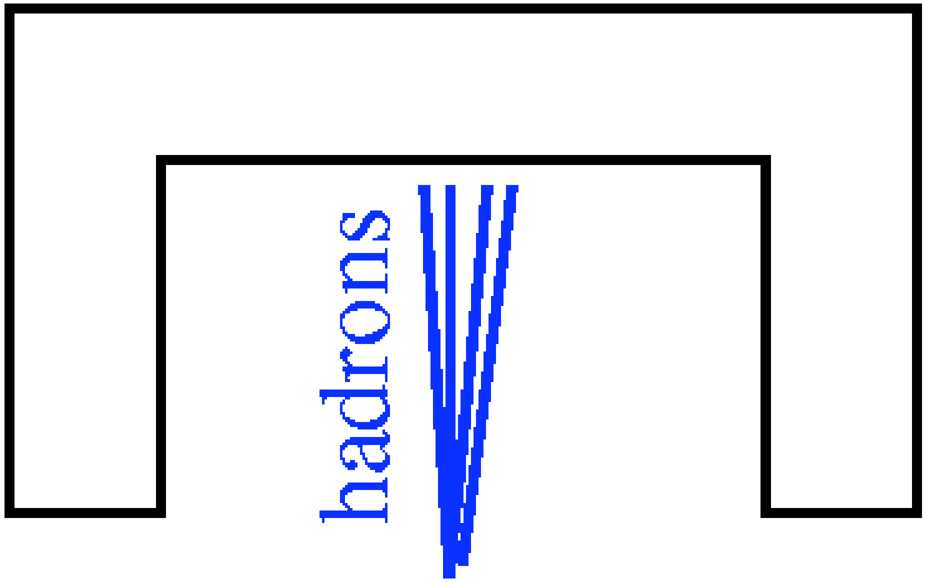
- Disclaimer:
  - Most discussion here valid for cone jets
    - Will make some comments on k_T jets
  - Will discuss CDF and D0 procedures as examples
    - ATLAS and CMS have no settled yet

Partons are produced in hard scatter



- Would like to know the energy of these partons

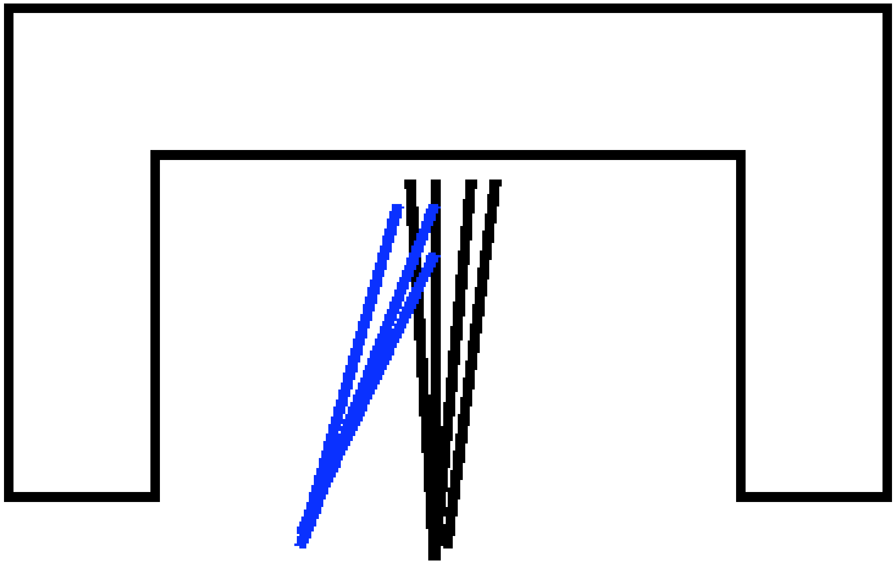
The parton will hadronise

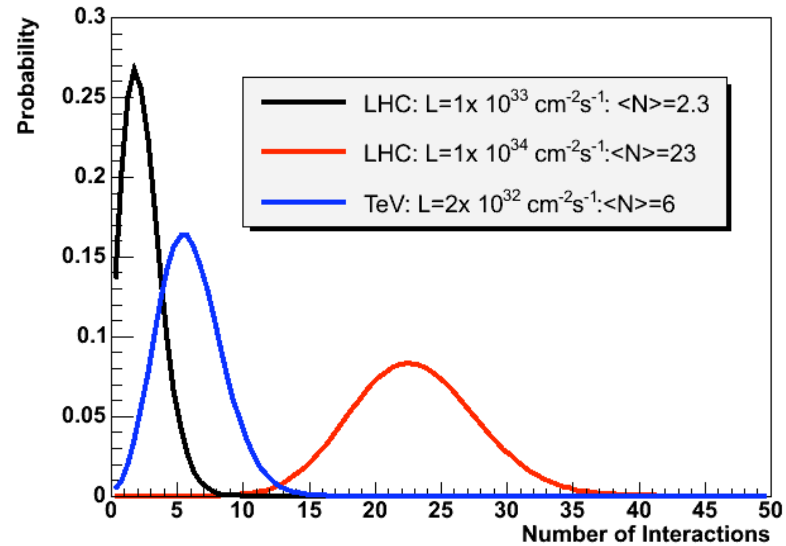


- Hadronization is non-perturbative QCD phenomenon:
  - Phenomenological models implemented in MC:
    - Lund-Strong Model: PYTHIA
    - Cluster fragmenation: HERWIG

Depends on energy and quark type

Multiple pp Interactions

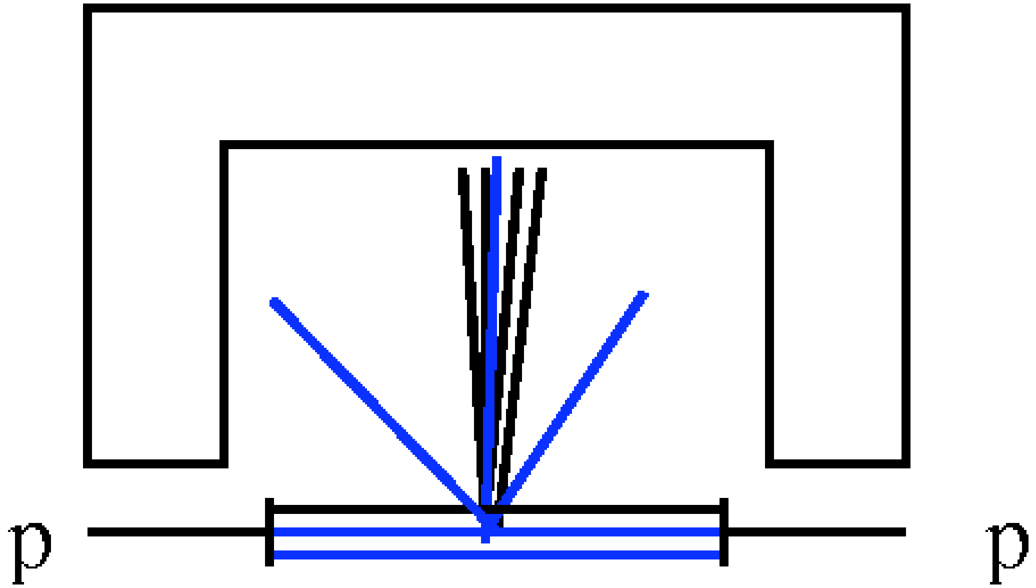




- Overlapping interactions can overlap the jet
- Number of extra interactions depends on luminosity
  - LHC:
    - Low lumi (L=1x10^{33} cm^{-2}s^{-1}): <N>=2.3
    - High lumi (L= 1x10^{34} cm^{-2}s^{-1}): <N>=23
  - Tevatron:
    - L= 2x10^{32} cm^{-2}s^{-1}: <N>=6

Offset depending on number of interactions

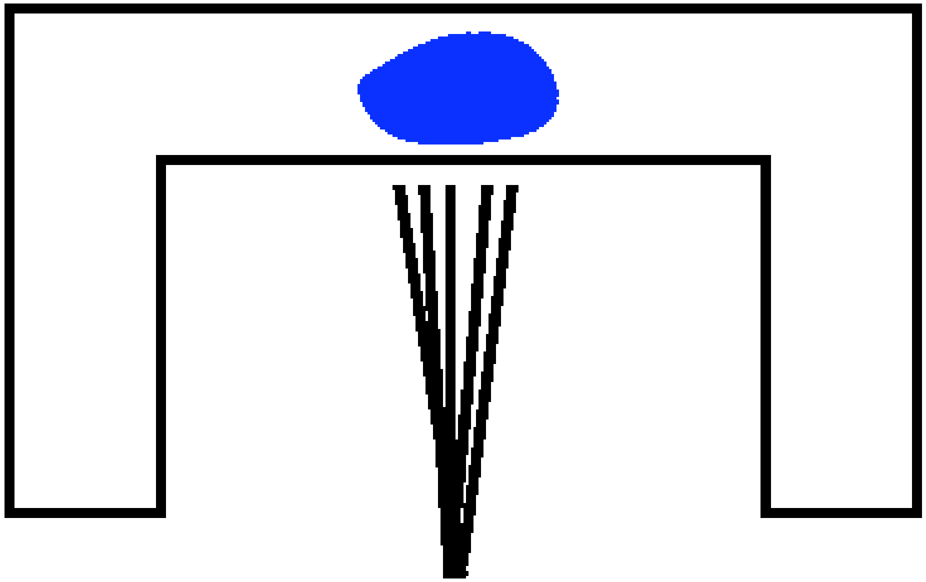
More than one parton per proton interacts



- Spectator partons can interact also and put energy into the same area as hard interaction

Offset, can depend on physics process

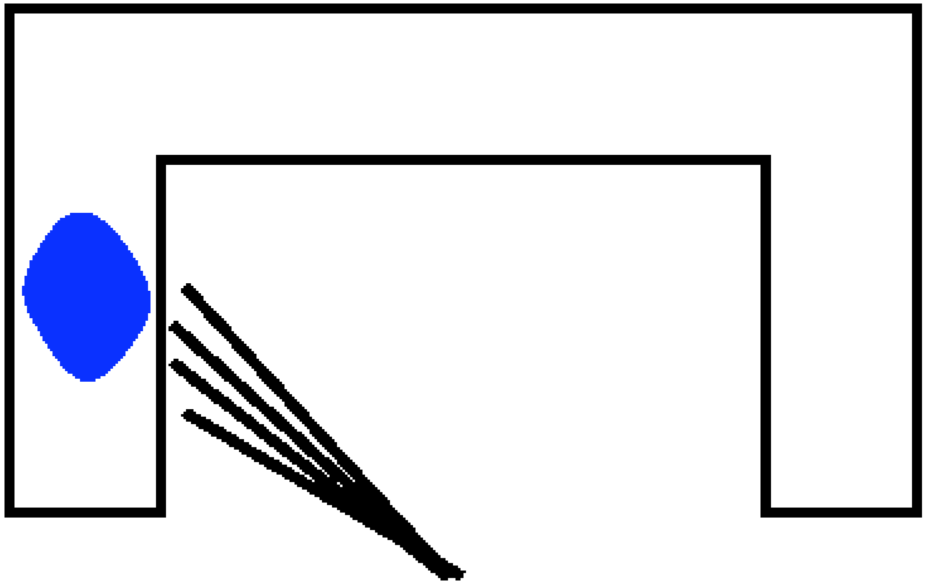
Hadrons enter calorimeter



- Calorimeter response determines what we measure

Correction depends on jet energy

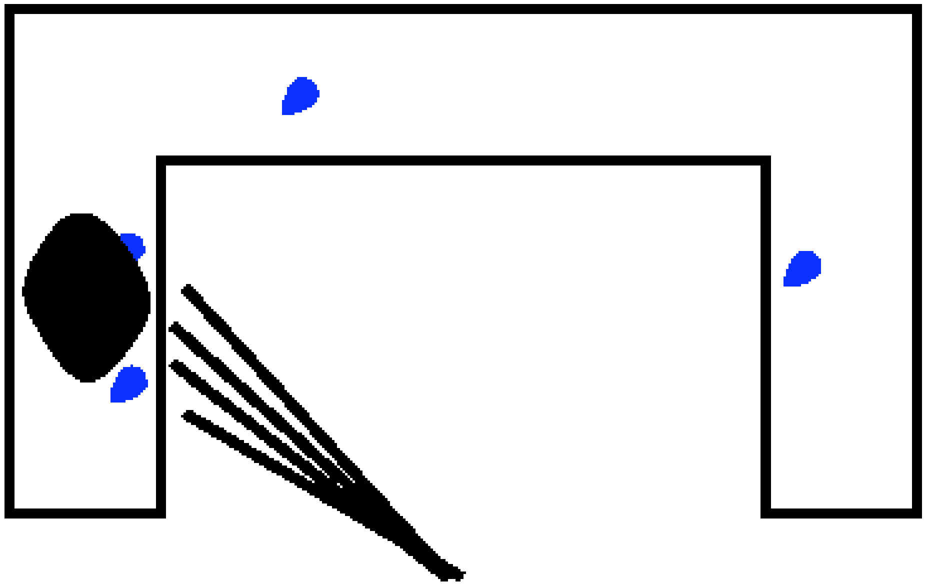
Calorimeter response depends on angle



- Often calorimeters are different in forward vs central region
- There are often poorly instrumented regions (cracks) that have lower response

Correction depends on jet angle and energy

Noise can overlap with jet

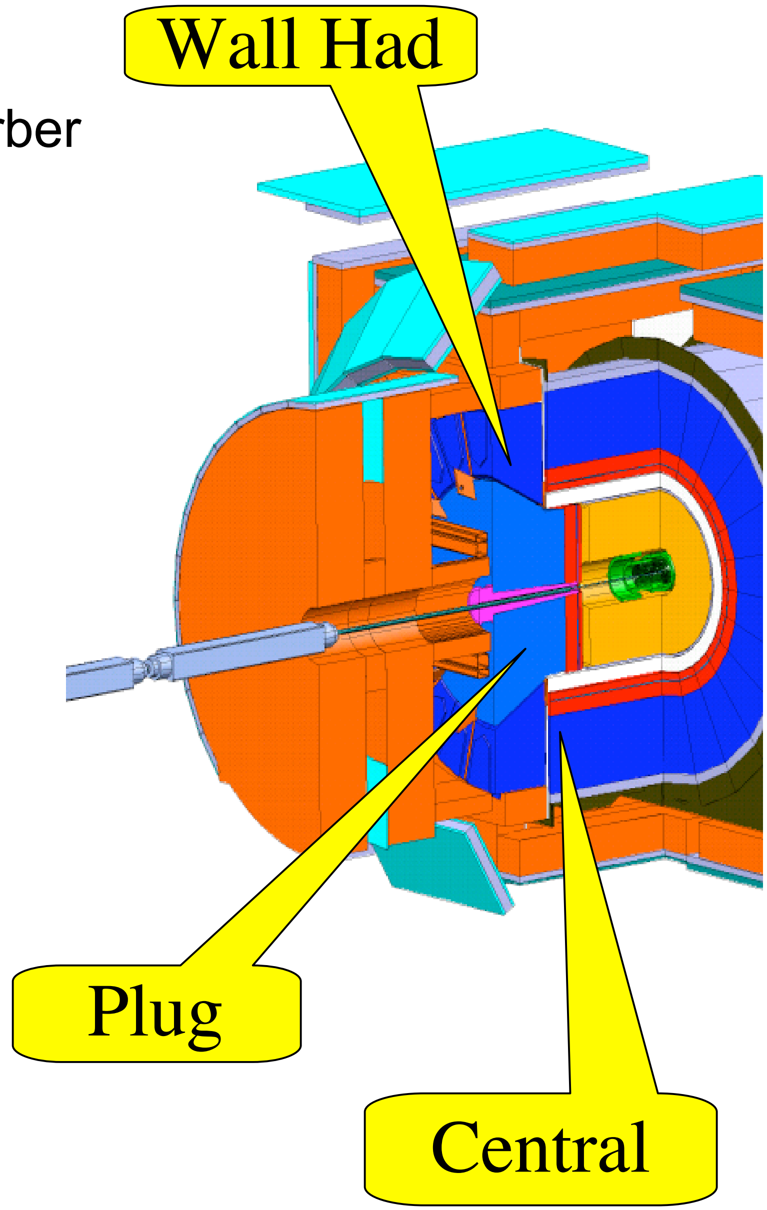


- Depending on noise level in calorimeter the noise overlapping with our jet can be significant

Offset depending on calorimeter noise level

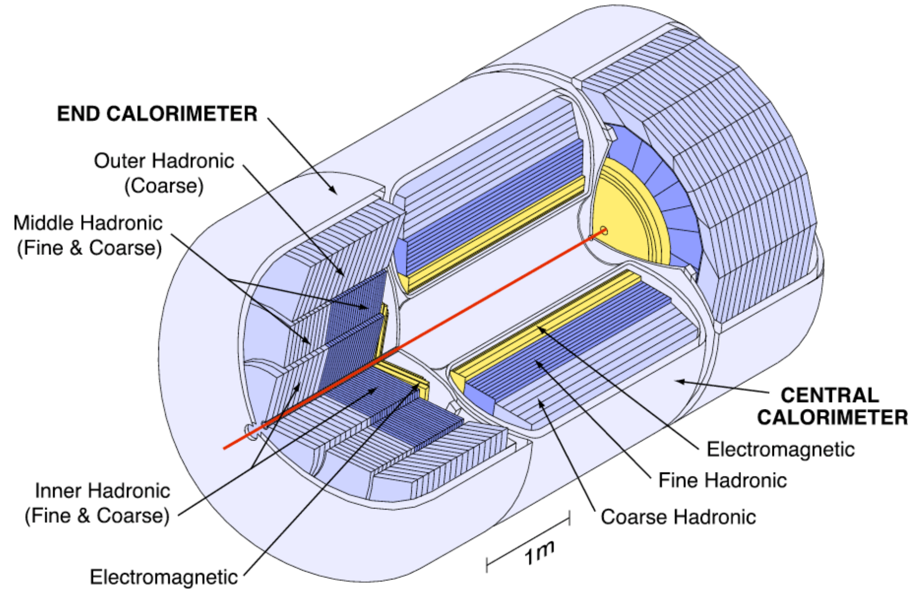
CDF calorimeter

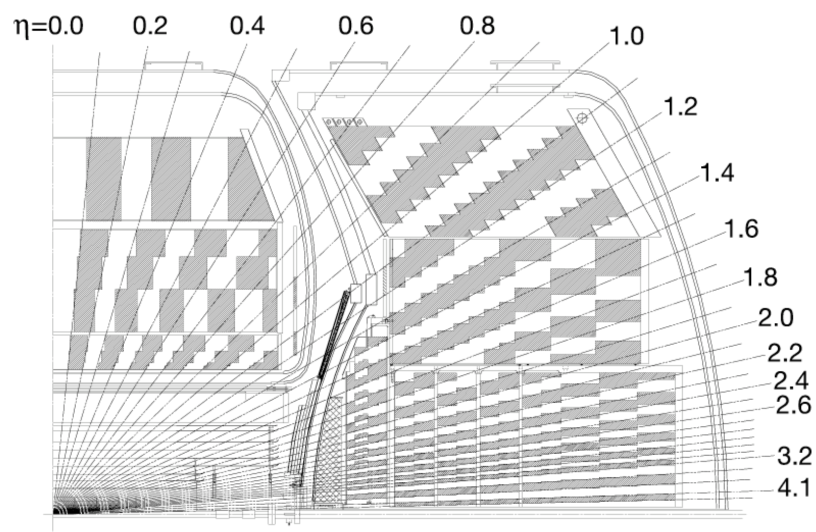
- Central and Wall ($|\eta|<1.2$):
  - Scintillating tile with lead (iron) as absorber material in EM (HAD) section
  - Coarse granularity: ~800 towers
  - Non-compensating
    - non-linear response to hadrons
  - Rather thin: 4 interaction lengths
  - Nearly no noise
  - Resolutions:
    - EM energies: $\sigma/E=13.5\% / \sqrt{E} \oplus 1.5\%$
    - HAD energies: $\sigma/E=50\% / \sqrt{E} \oplus 3\%$
- Plug ($1.2<|\eta|<3.6$):
  - Similar technology to central
  - Resolution:
    - EM energies: $\sigma/E=16\ \% / \sqrt{E} \oplus 1\%$
    - HAD energies: $\sigma/E=80\ \% / \sqrt{E} \oplus 5\%$
  - Thicker: 7 interaction lengths



DØ Calorimeter

- Same technology in central and forward calorimeter:
  - Liquid Argon with iron (steal) as absorber in EM (HAD) calorimeter
  - Fine granularity: ~50K cells
  - Depth:
    - 7.2-8.0 interaction lengths
  - Compensating:
    - Compromised in Run 2:
      - Integrate charge only in 260ns due to shorter bunch spacing
  - Resolutions:
    - EM energies: $\sigma/E = 15\% / \sqrt{E} \oplus 0.3\%$
    - HAD energies: $\sigma/E = 50\% / \sqrt{E} \oplus 4\%$

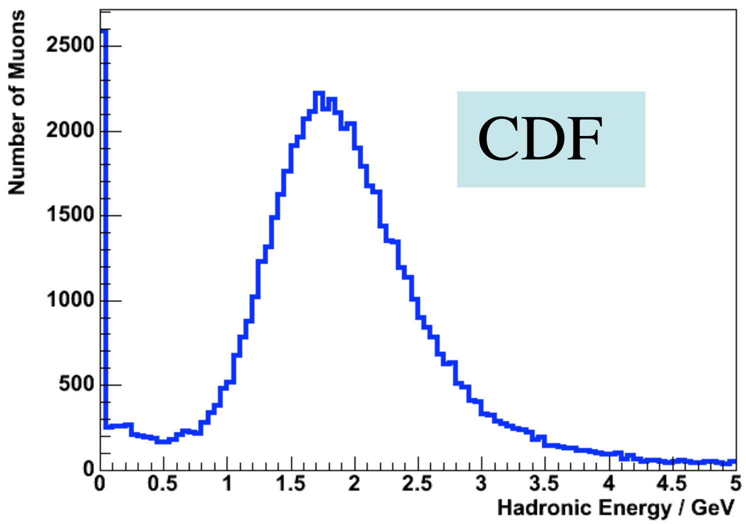


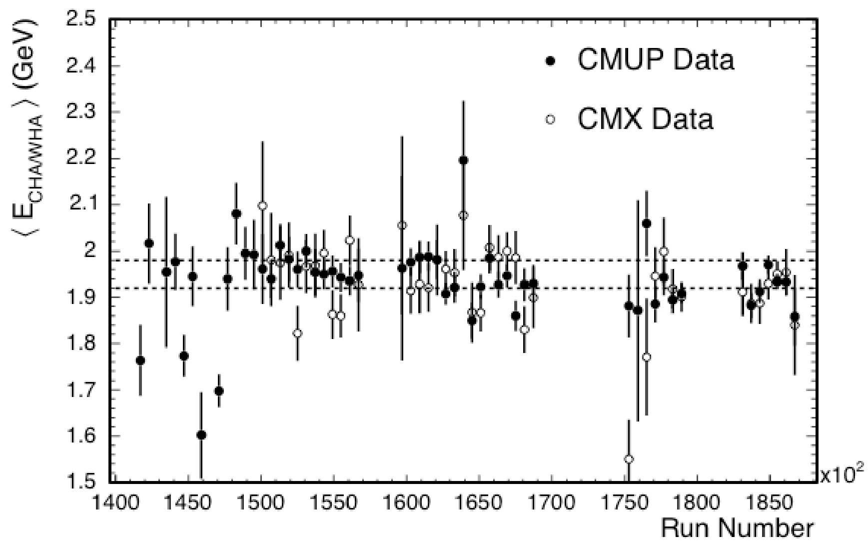


Online calibration: see N. Hadley's lecture

In Situ Calorimeter Calibration: Hadronic Energy

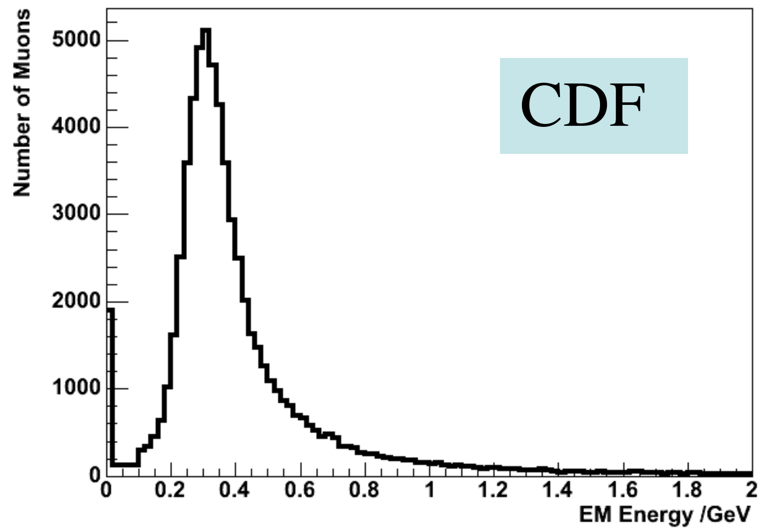
- Minimum Ionising Particle (MIP):
  - J/ψ and W muons
  - peak in HAD calo: ≈2 GeV (in CDF)
  - Check time stability
- Minimum bias events
  - E.g. $N_{tower}(E_T>500\text{ MeV})$

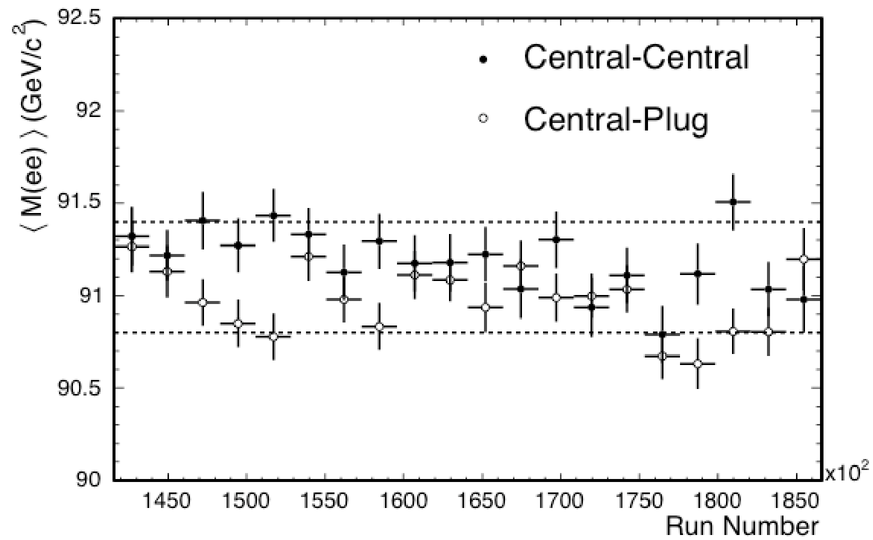




In Situ Calorimeter Calibration: EM Energy

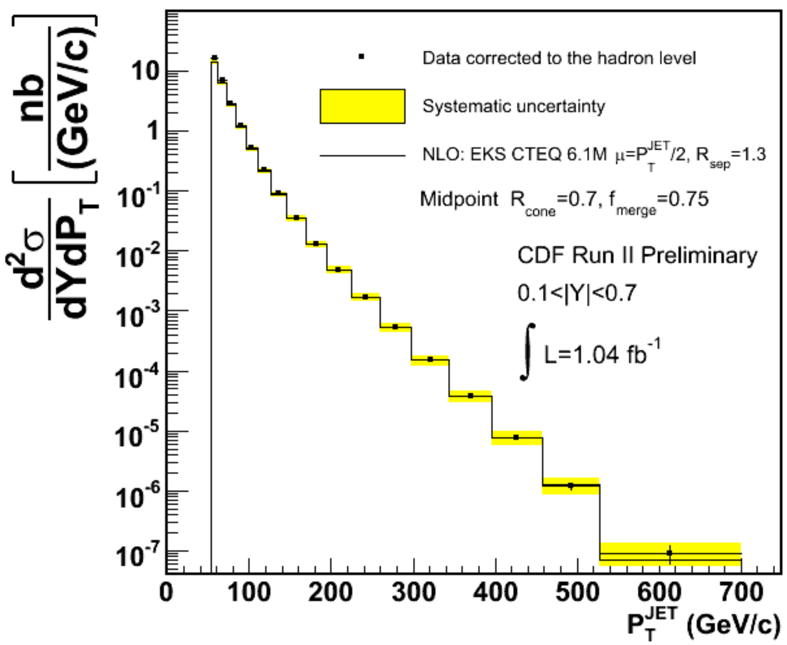
- MIP peak:
  - If visible (CDF at 300 MeV)
- Z→ ee peak:
  - Set absolute EM scale in central and plug
- E/p for electrons
  - After having calibrated p and material (see M. Shapiro's lecture)
- Minimum Bias events:
  - Occupancy above some threshold: e.g. 500 MeV

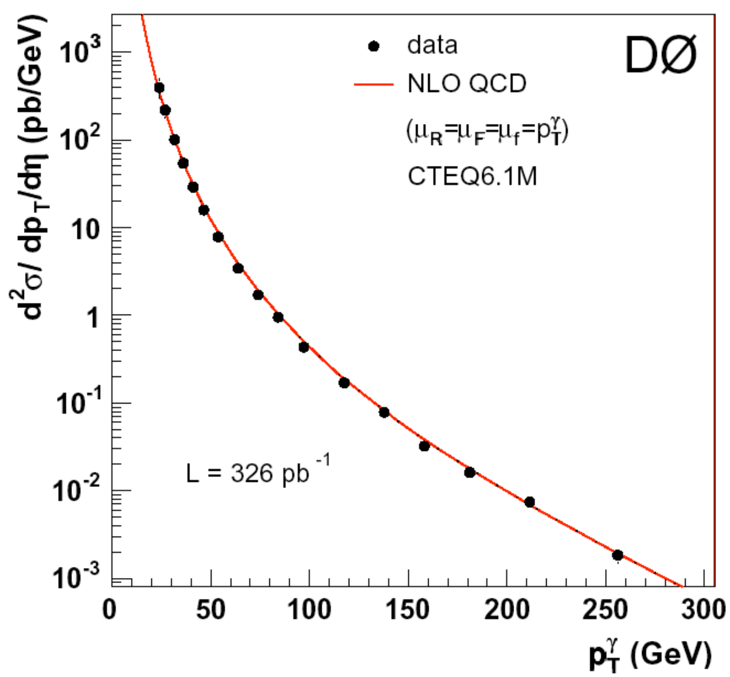




Calibrating jets at a Hadron Collider

- Hadron collider:
  - Physics processes span entire jet E_T range: $0<E_T<\sqrt{s}/2$
  - Calibration processes (photon-jet) run out of steam much earlier:
    - E.g. $d\sigma(\gamma)/dp_T = 0.001\ d\sigma(\text{jet})/dp_T$
  - Unlike at HERA (NC process) or LEP/SLC (Z-resonance)





Two different approaches

- CDF and DØ use very different approaches
  - Documented in
    - CDF Run 2: hep-ex/0510047 (accepted by NIM)
    - DØ Run 1: NIM A424: 352-394 (1999)
    - DØ Run 2: http://www-d0.fnal.gov/phys_id/jes/public/plots_v7.1/index.html
- Main difference:
  - CDF uses test beam and single particles measured in-situ to understand absolute response of single particles
    - deduce jet response using simulation
    - Cross check with calibration processes like photon-jet data
  - DØ uses photon-jet data to measure absolute response
    - Extra correction for "showering" necessary
- Other differences:
  - CDF corrects separately for underlying event, multiple interactions, out-of-cone energy
  - DØ includes all these effects into one correction factor

Overview: CDF and DØ

- CDF calibrates P_T

$$P_{T,jet}^{corr} = \frac{P_{T,jet}^{raw} \times F_\eta - MI}{R}$$

- P_T^{corr}: calibrated jet P_T
- P_T^{raw}: raw jet P_T
- F_η: eta-dependent correction
- R: absolute response
- MI: multiple interactions

- DØ calibrates Energy

$$E_{jet}^{corr} = \frac{E_{jet}^{raw} - O}{F_\eta \times R \times S}$$

- E^{corr}: calibrated jet E
- E^{raw}: raw jet E
- F_η: eta-dependent correction
- R: absolute response
- O: offset energy
  - includes MI, noise, UE
- S: showering corrections

- Systematic error associated with each step
- additional corrections to get to parton energy

CDF: Detector to Particle Level

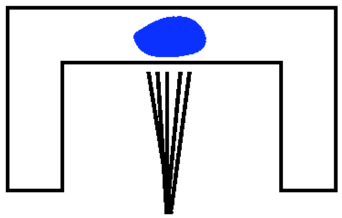
- Do not use data since no high statistics calibration processes at high E_T>100 GeV
- Extracted from MC ➔ MC needs to

1. Simulate accurately the response of detector to single particles (charged pions, photons, protons, neutrons, etc.):
   CALORIMETER SIMULATION
   (CDF uses fast parameterization GFLASH, D0 uses GEANT3)
2. Describe particle spectra and densities at all jet Et:
   FRAGMENTATION

– Measure fragmentation and single particle response in data and tune MC to describe it

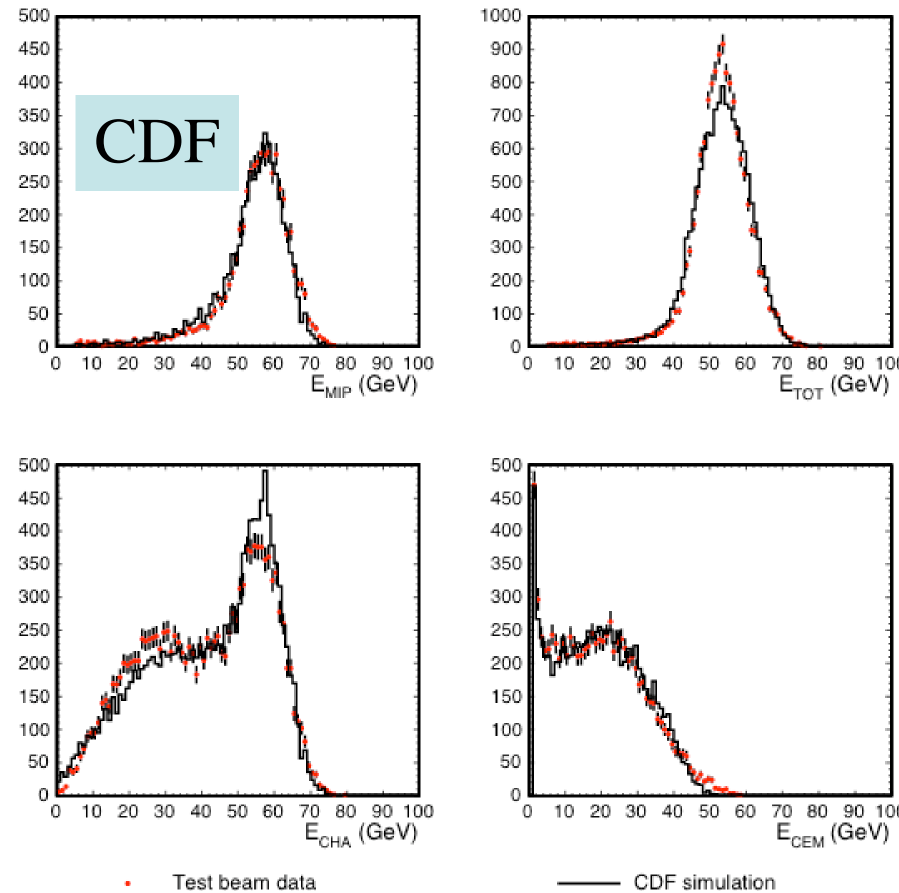
– Use MC to determine correction function to go from observed to “true”/most likely Et:

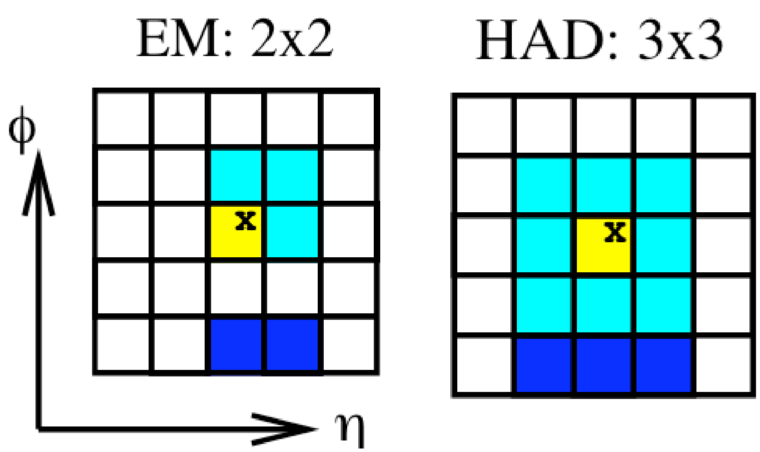
$$E^{true}=f\ (\ E^{obs},\ \eta,\ \text{conesize})$$

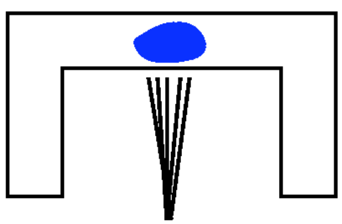


Single Particle Response Simulation

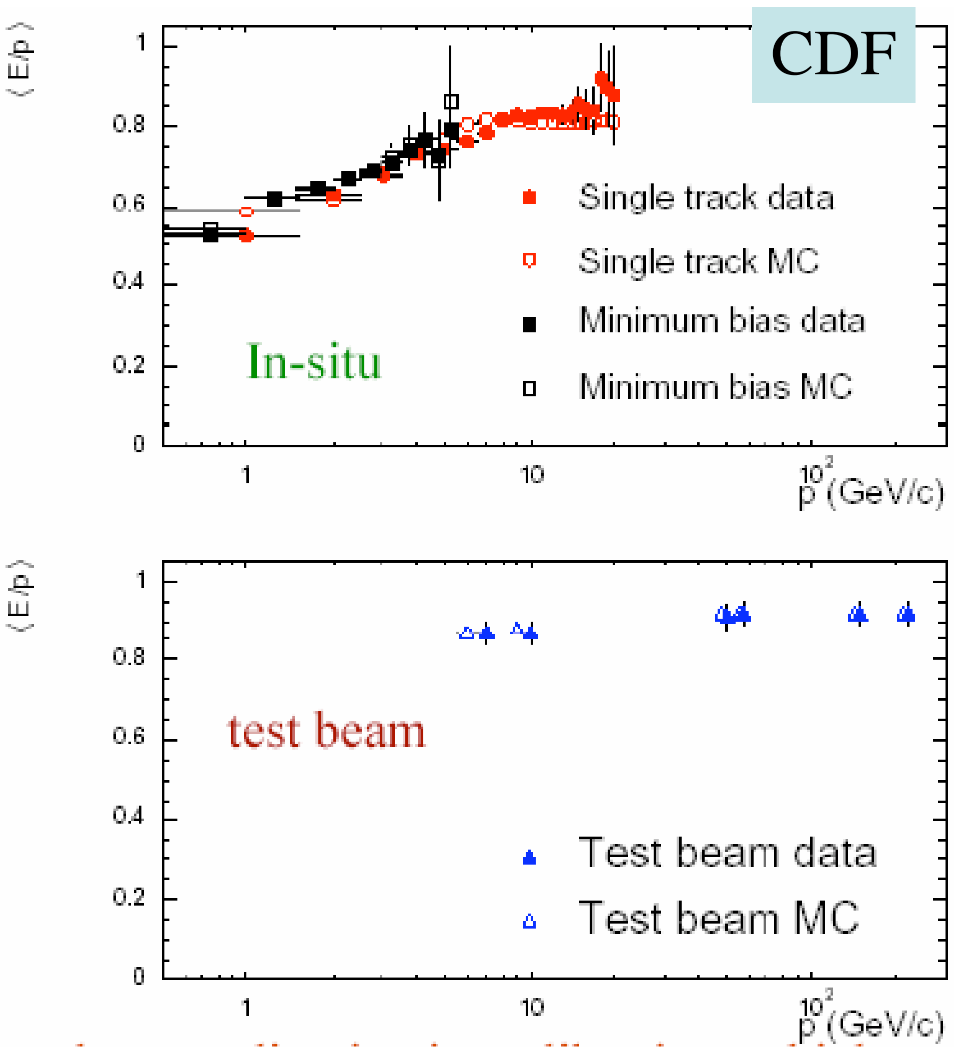
- Single particle response:
  - Test beam
  - In situ:
    - Select “isolated” tracks and measure energy in tower behind them
    - Dedicated trigger
    - Perform average BG subtraction
  - Tune simulation to describe E/p distributions at each p (use π/p/K average mixture in MC)

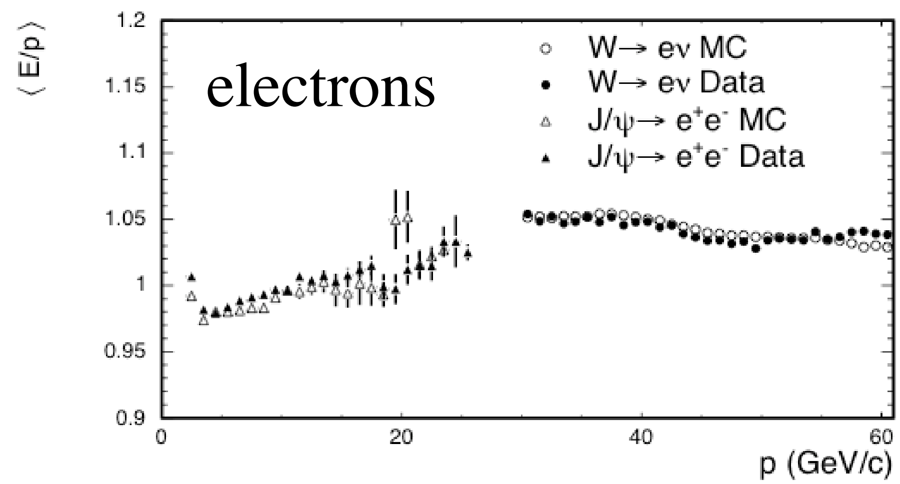






Single Particle Response Simulation





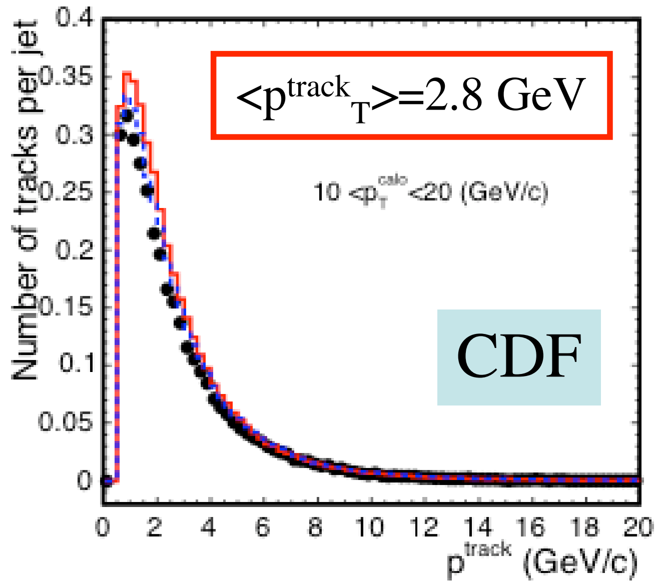
Typical jet composition:
- 60% charged particles
  - 10% protons
  - 90% pions
- 30% neutral pions ($\rightarrow\gamma\gamma$)
  - EM response
- 10% other (neutrons,…)

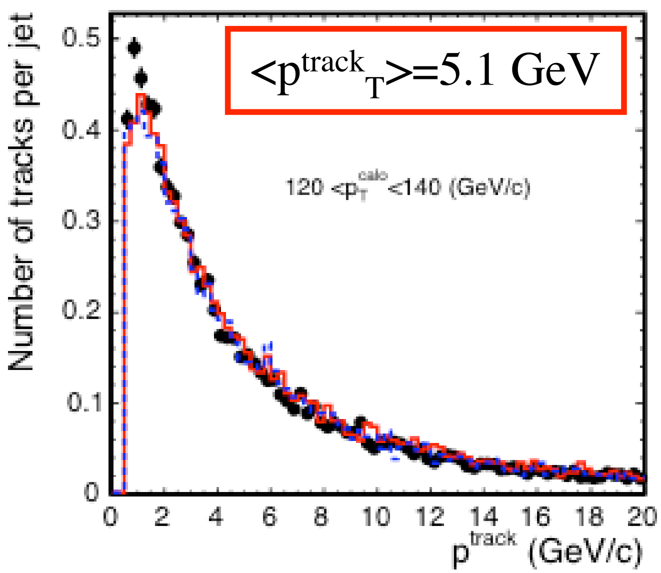
- MC models
  - Hadron response at low p_T (in situ data) and high p_T (test beam data)
  - Electron response

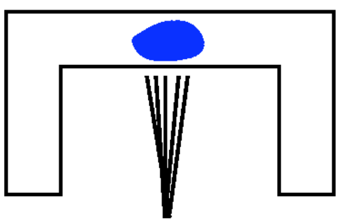
Fragmentation

- Due to non-linearity of calorimeters big difference between e.g.
  - one 10 GeV pion: ~8 GeV
  - ten 1 GeV pions: ~ 6 GeV

- Measure P_T spectra of particles in jets at different E_T values as function of track P_T:
  - Typically mean rather low
  - Requires understanding track efficiency inside jets

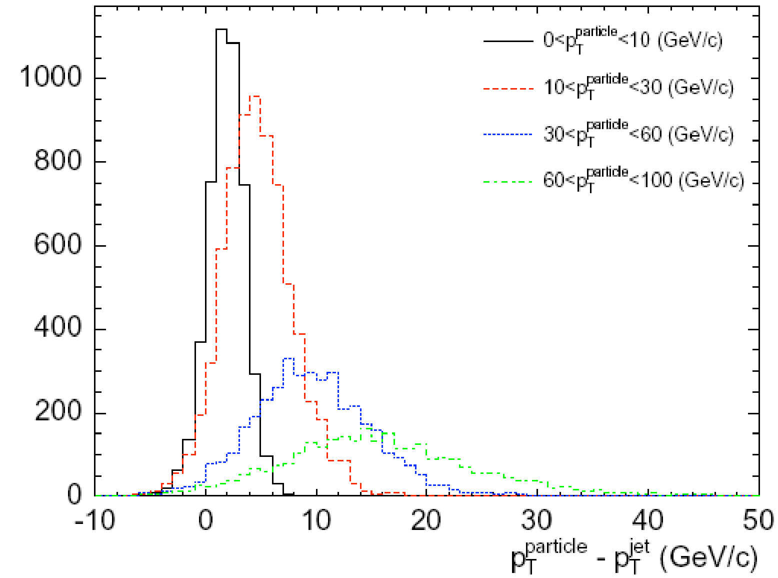


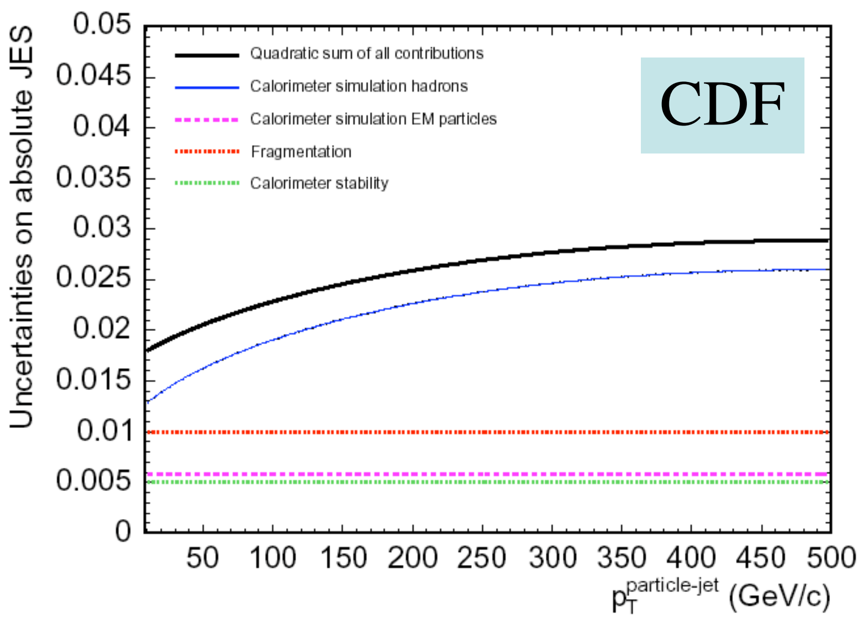


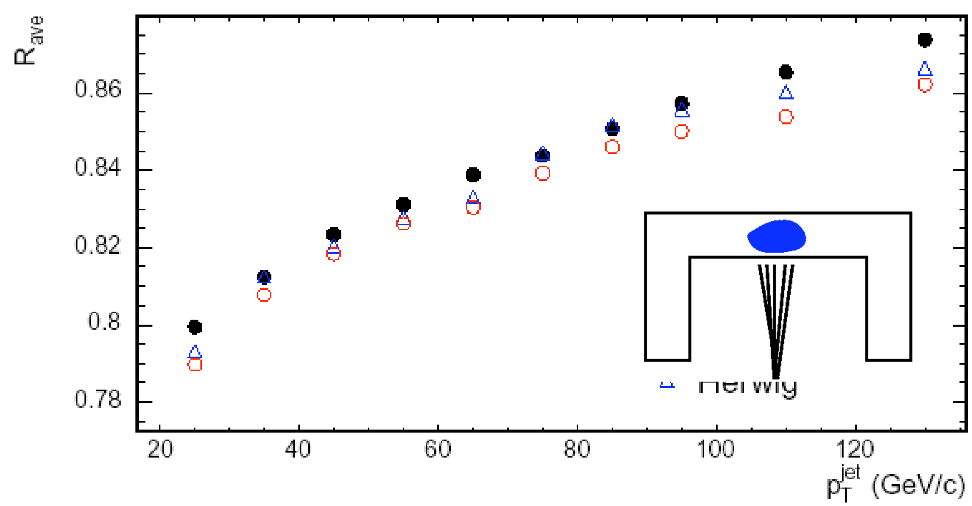


Jet Correction to Particle Level

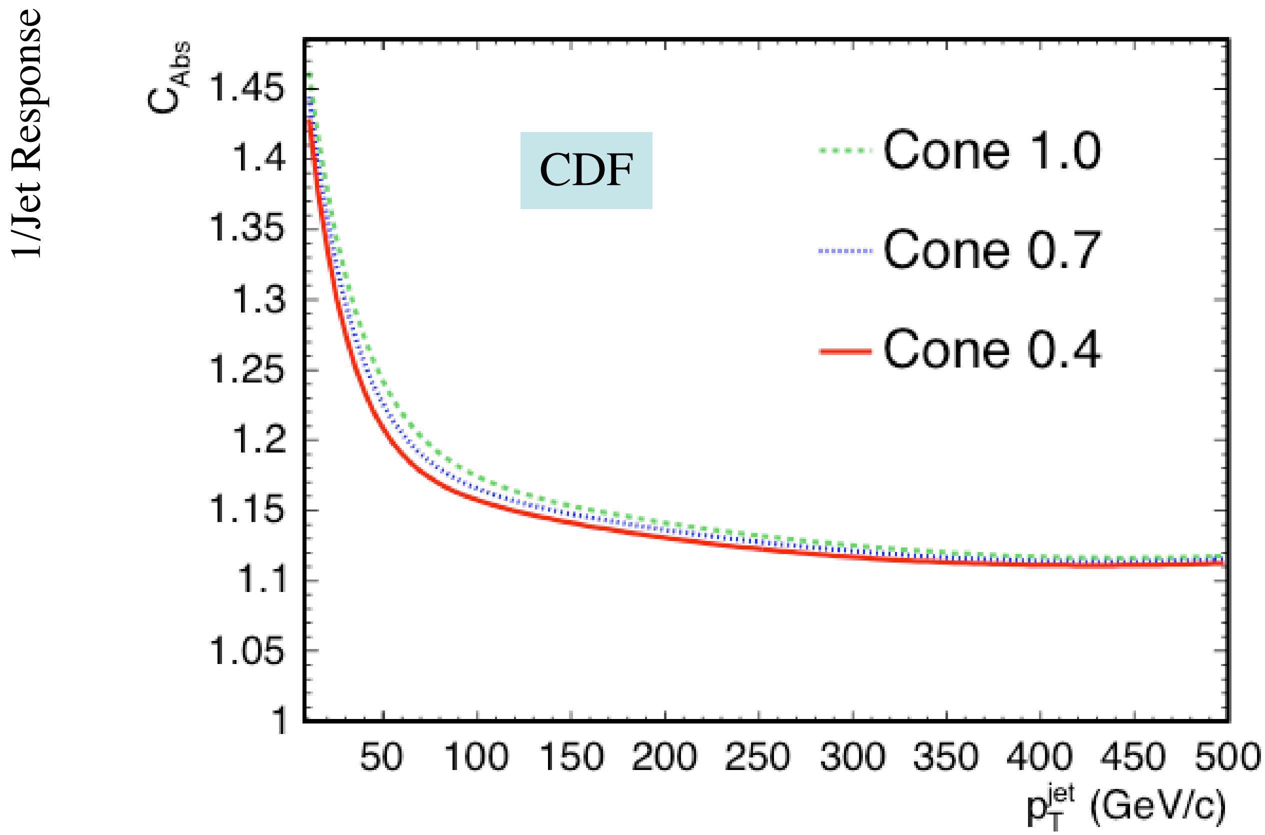
- MC convolutes response and particle momentum spectrum for us
  - Use tuned and validated MC to compare measured jet to jet at particle level
  - systematic uncertainty given by how well MC simulation and fragmentation reproduced data

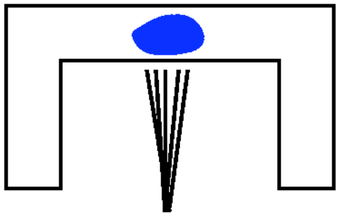






CDF: Absolute Calorimeter Response

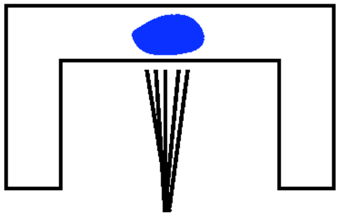


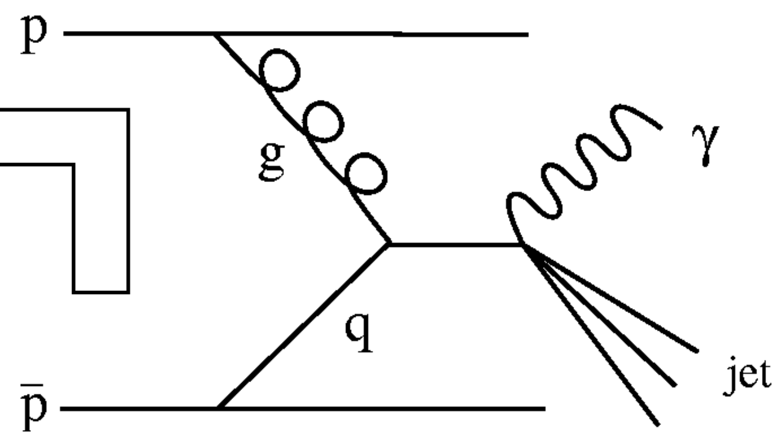


- Nearly independent of cone size
  - Response about 80% at p_T=50 GeV, 87% at p_T=300 GeV

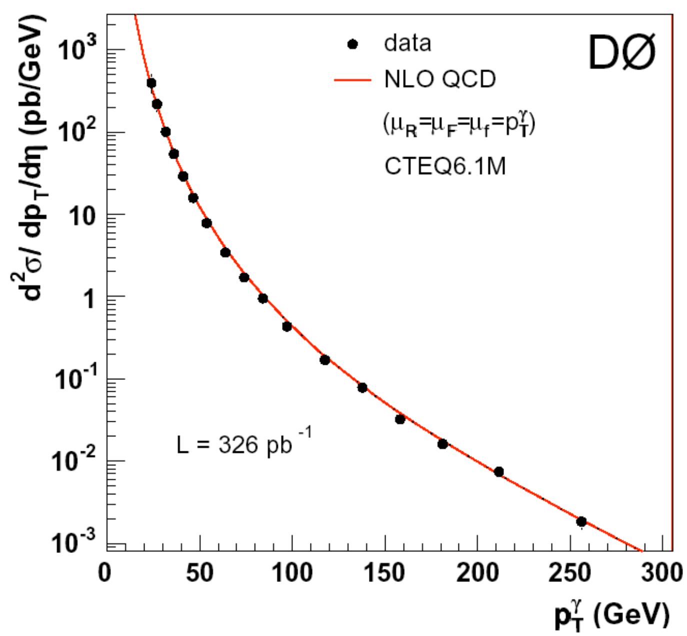
Response correction using prompt photons

- Prompt photon process:
  - Photon well measured in calorimeter
    - Calibrated using electrons
  - Constraint: $E_T(\gamma)=E_T(\text{jet})$



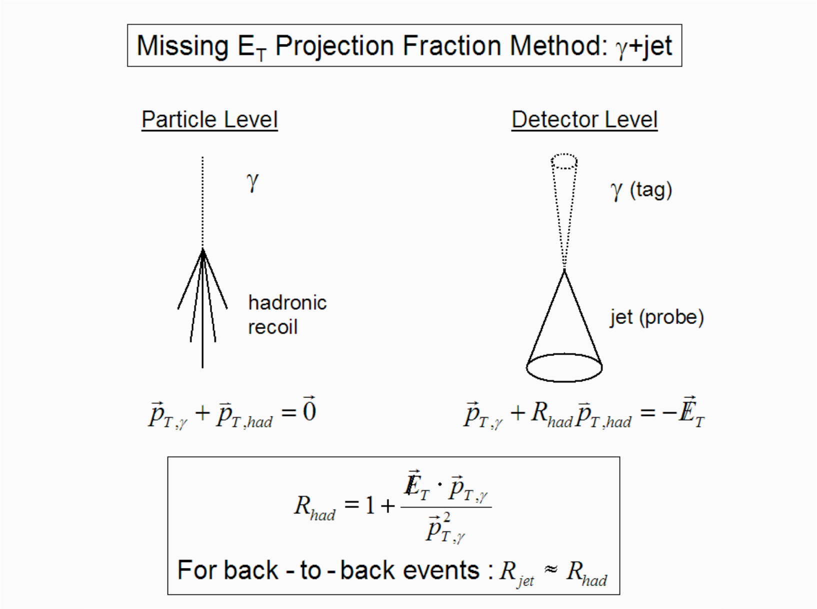


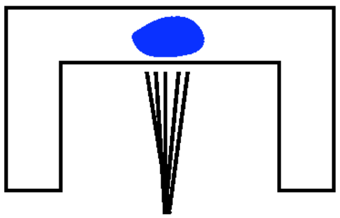
- Complications:
  - Number of events at high E_T rather low:
    - $E_T(\gamma)>300$ GeV, $\int L dt=1$ fb^{-1}: 40 events
  - Background due to π^0's
    - Purity: 30-80% for $E_T(\gamma)$=20-100 GeV
  - Higher order processes:
    - Photon + 2 jets

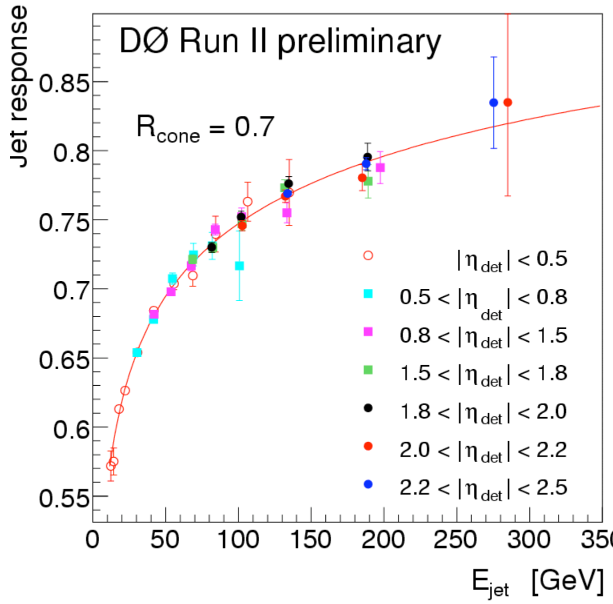


DØ using prompt photons

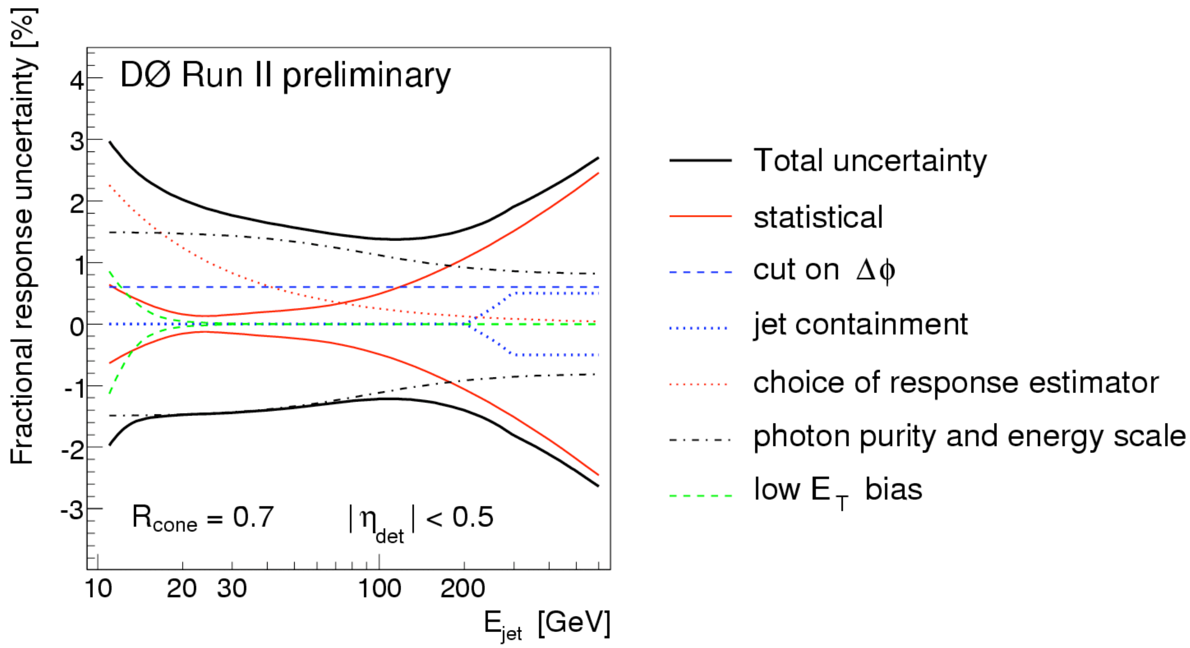
- Reduce "physics effects":
  - "MPF method":
    - MPF=Missing Et Projection Fraction
  - Require jet to be back-to-back with photon:
    - $\Delta\phi$>3 radians (>172°)
- Reach high $E_{T,jet}$:
  - Calibrate versus energy E_{jet}
    - Exploiting similarity between forward and central calorimeters
  - $\eta_{jet} \approx 0$: $E_{jet} \approx E_{T,jet}$
  - $\eta_{jet} \approx 2$: $E_{jet} \approx 3\ E_{T,jet}$



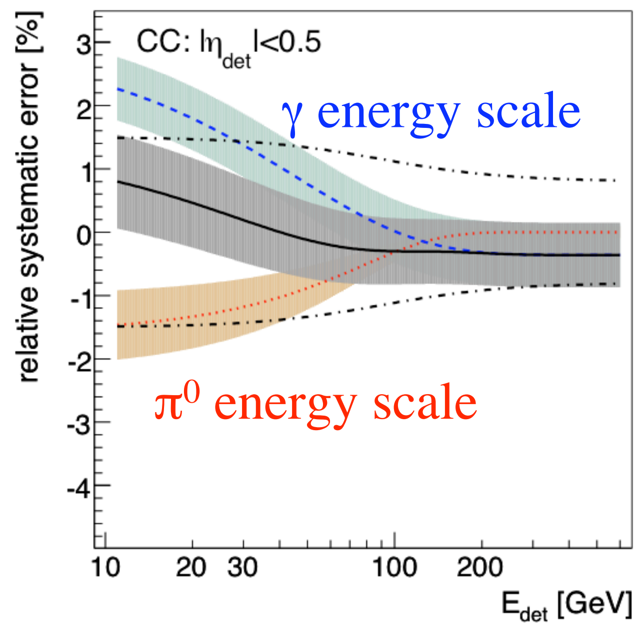




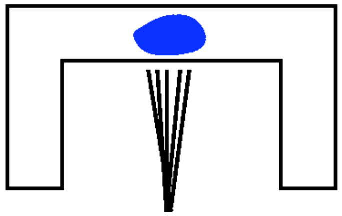
Syst. Uncertainties on Response



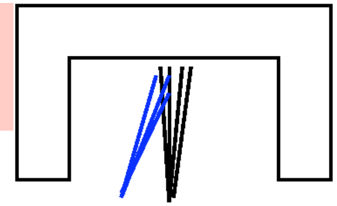
γ purity and scale syst.



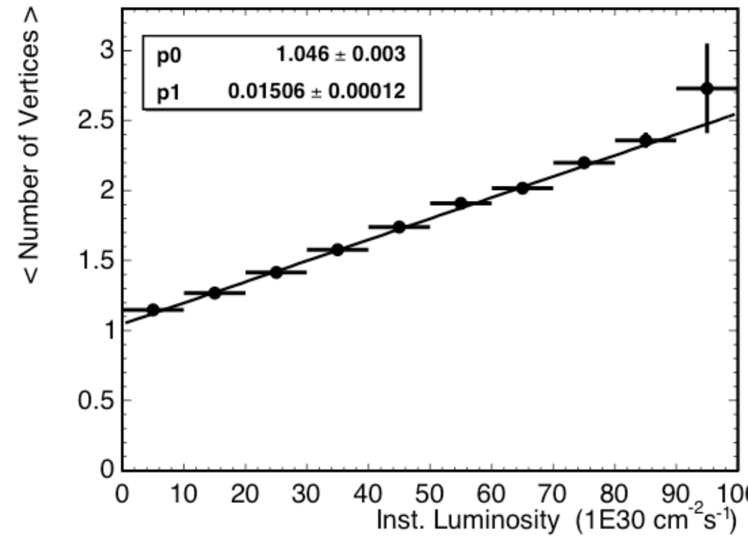
- Varying assumptions gives systematic uncertainty
- In analysis data/MC difference counts in most cases
  - Same procedure done for MC

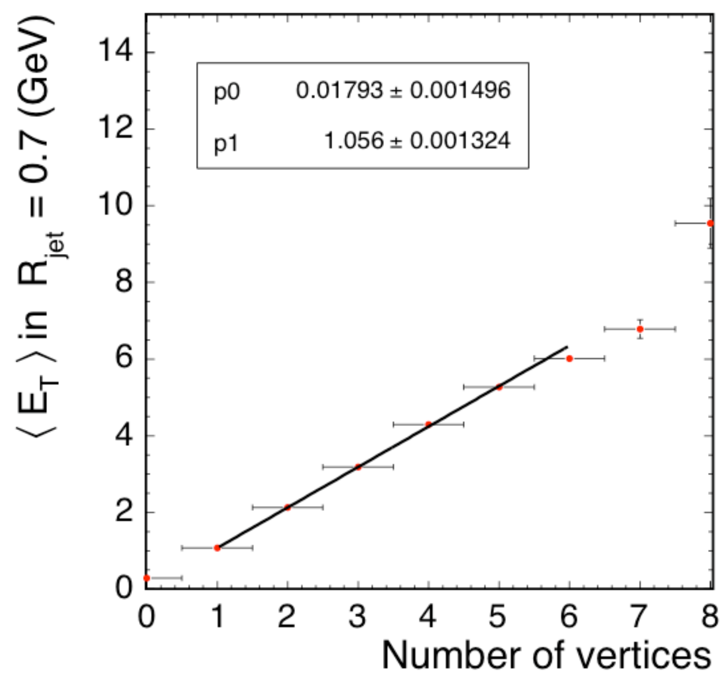


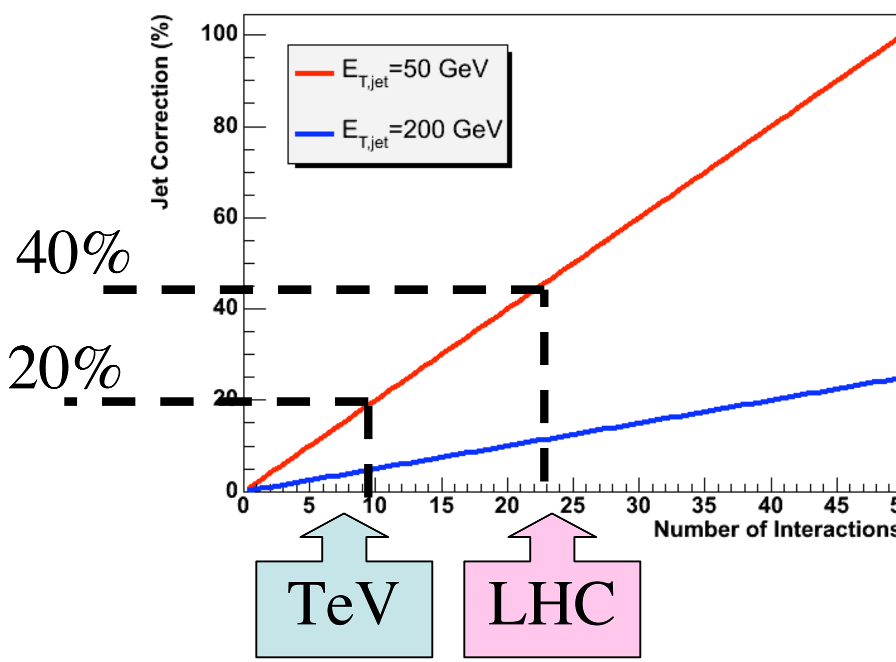
Multiple Interactions (MI)



- Need to know how many interactions there were:
  - # of z-vertices ~ # of interactions
- Throw random cones in Minimum Bias events
  - Determine average E_T per cone, e.g. CDF: 1 GeV for R=0.7

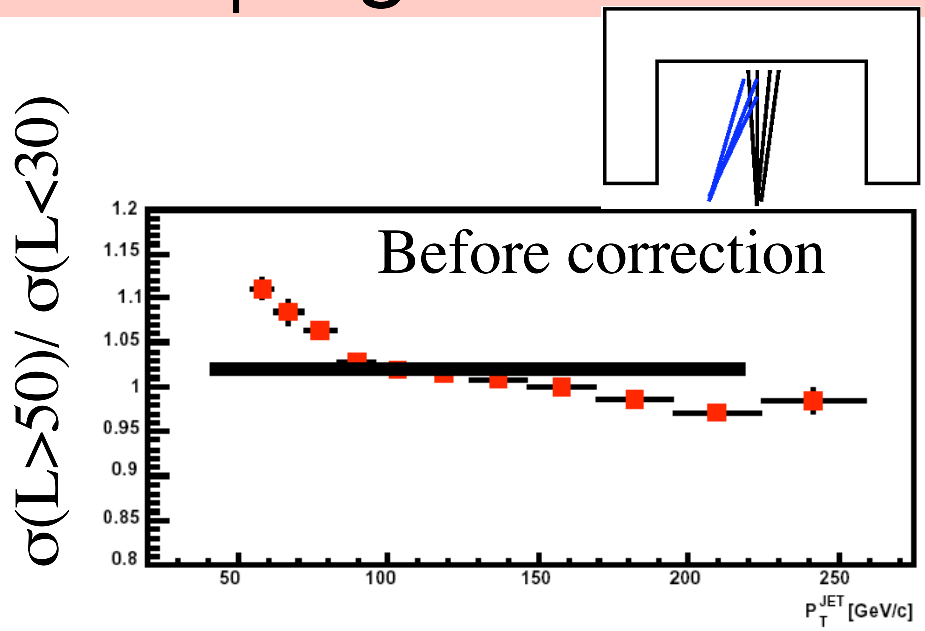


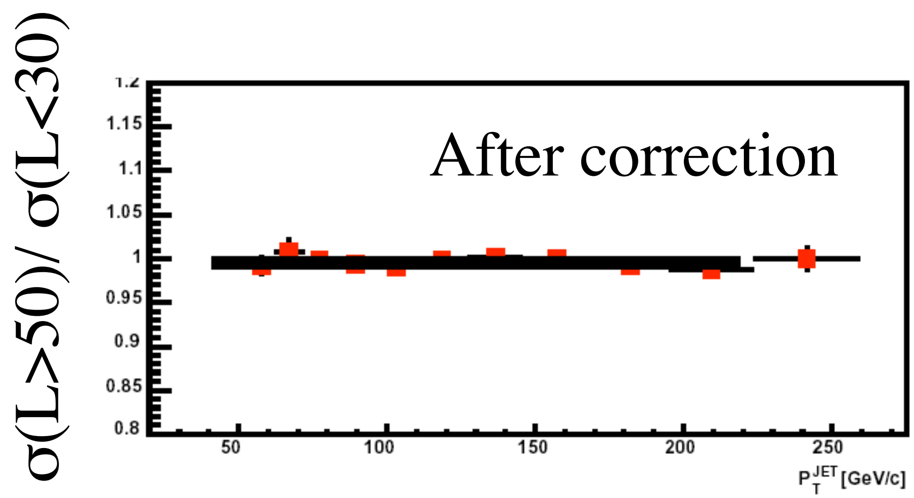




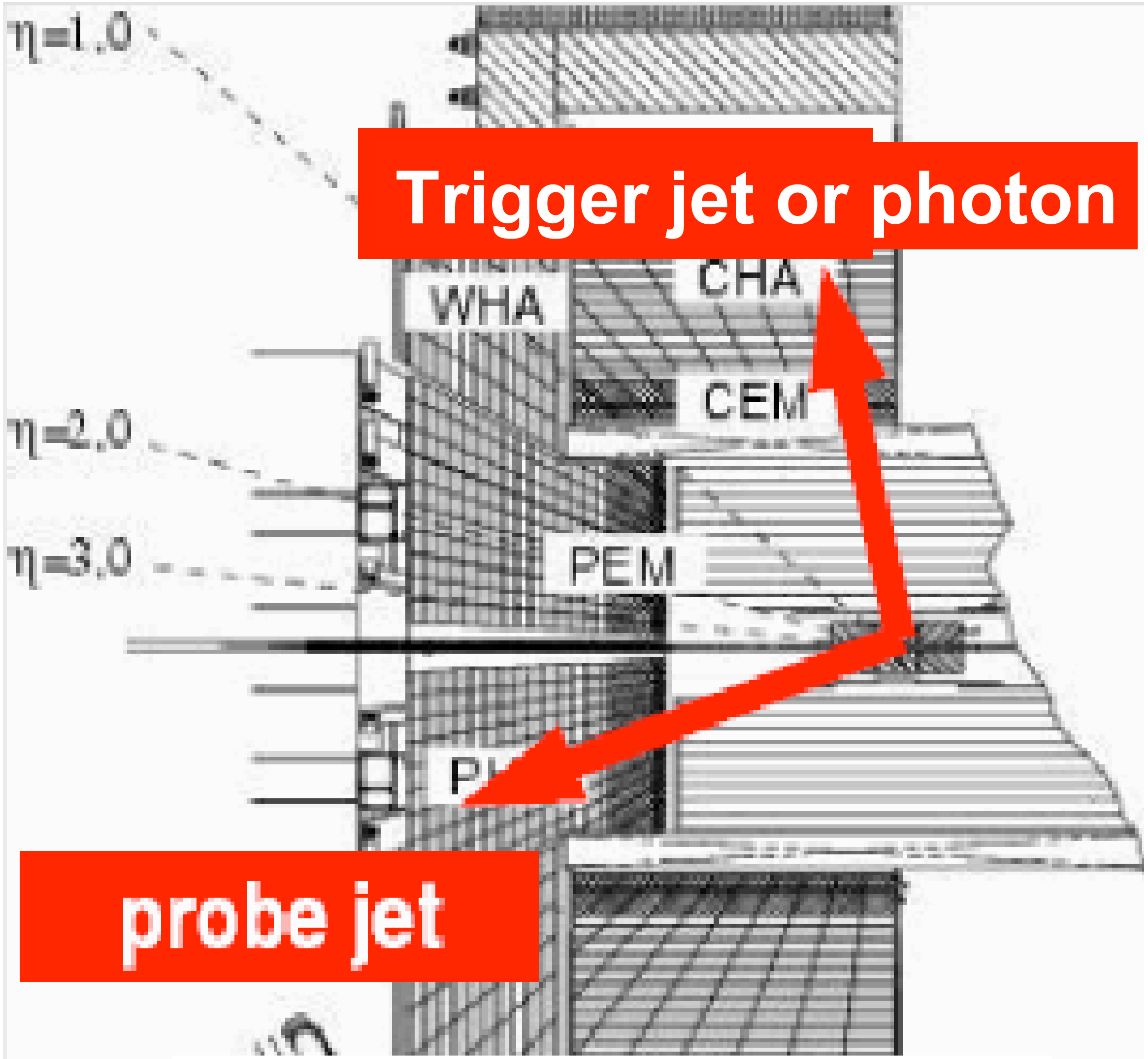
The complication for k_T algorithm

- Multiple Interactions are main reason for the difficulties with the k_T algorithm at hadron colliders
  - The method of throwing a random cone does not work:
    - they are not cone jets
  - k_T algorithm biases itself to go where the energy is and picks up energy from MI
- k_T algorithm has now been used by CDF in Run 2 for the jet cross section:
  - Empirical correction factor using fact that cross section independent of inst. luminosity





Relative Corrections

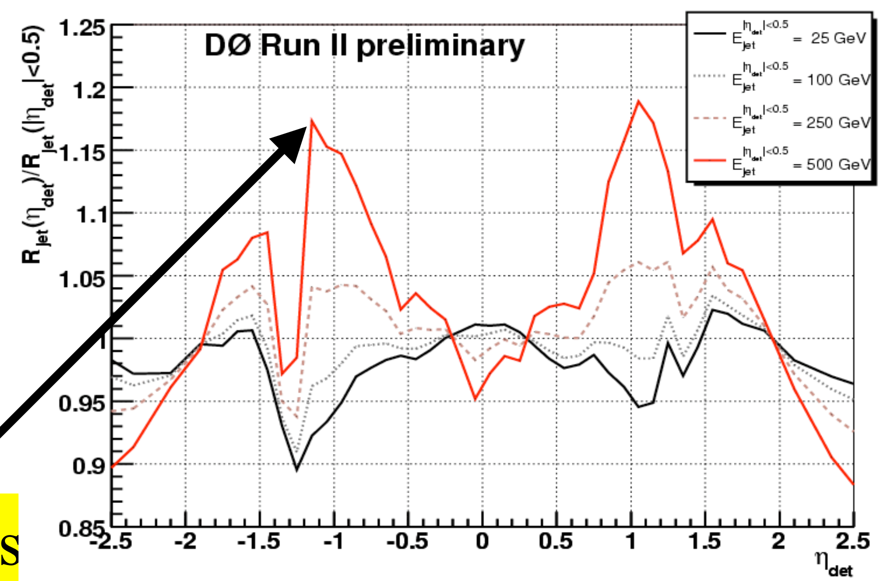


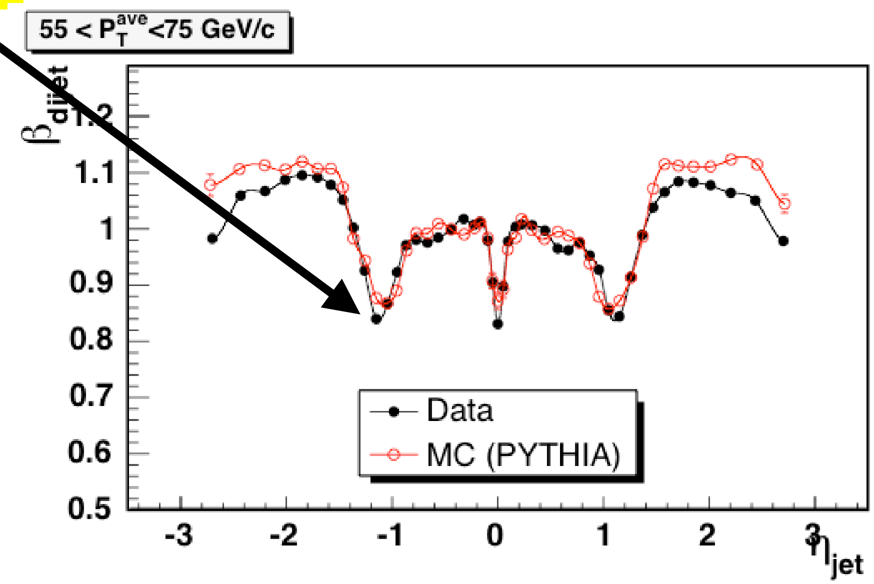
$$\beta = p_T^{probe} \;/\; p_T^{trigger}$$

Relative Corrections

- Mapping out cracks and response of calorimeter
- Central at ~1 by definition
- D0:
  - Response similar in central and forward
  - Two rather large cracks
- CDF:
  - Response of forward better than of central
  - Three smaller cracks
- Difficulties:
  - depends on E_T
  - Can be (most often is initially) different for data and MC

Cracks



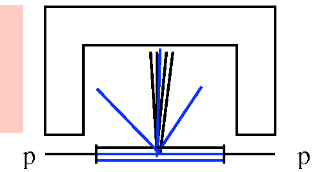


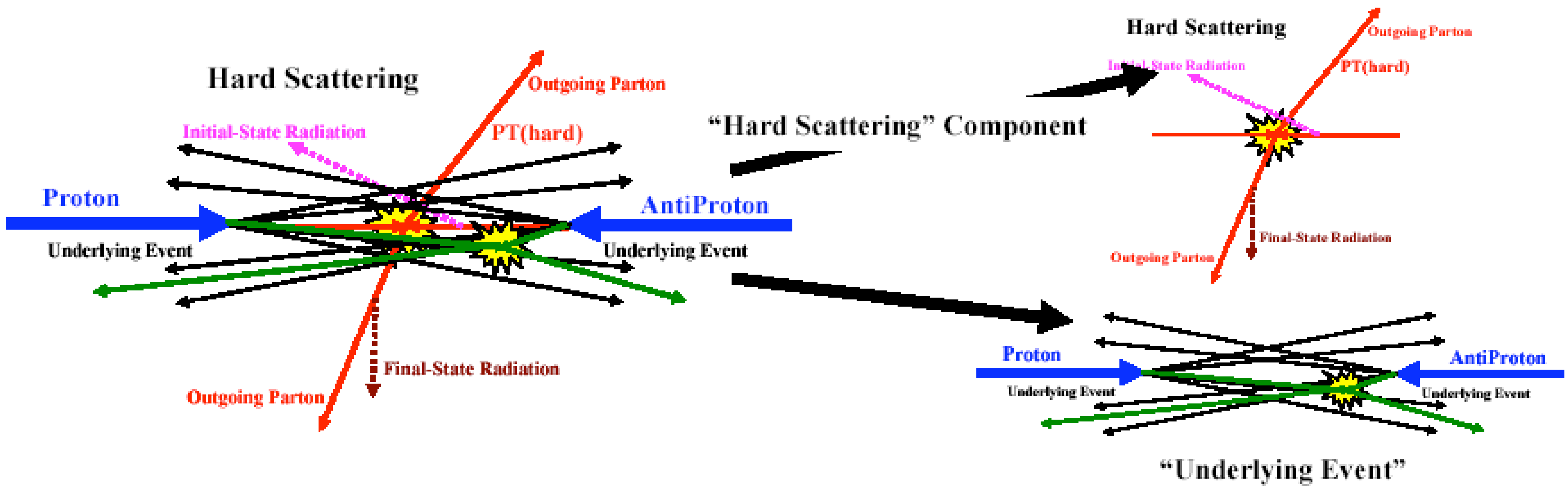
Corrections from Particle Jet to Parton

- Underlying event (UE) and Out-of-cone (OOC) energy
  - Only used if parton energy is wanted
  - Requires MC modeling of UE and OOC
    - Differences are taken as systematic uncertainty

$$P_{T,parton} = P_{T,particle} - UE + OOC$$

Underlying Event

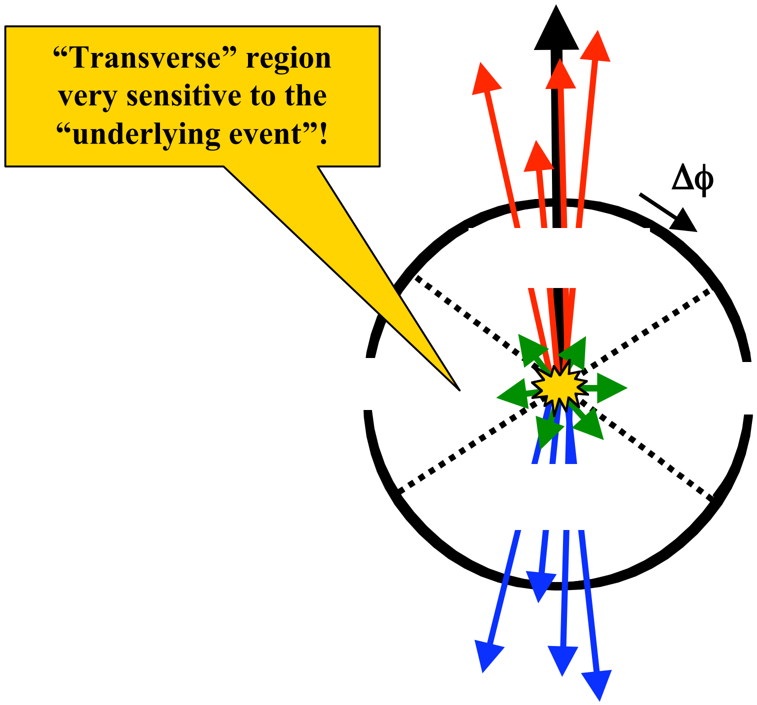


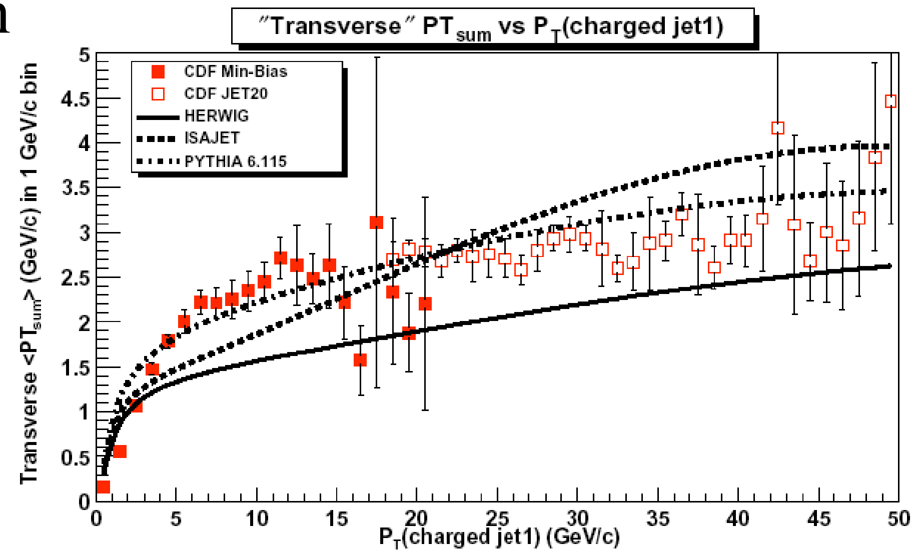


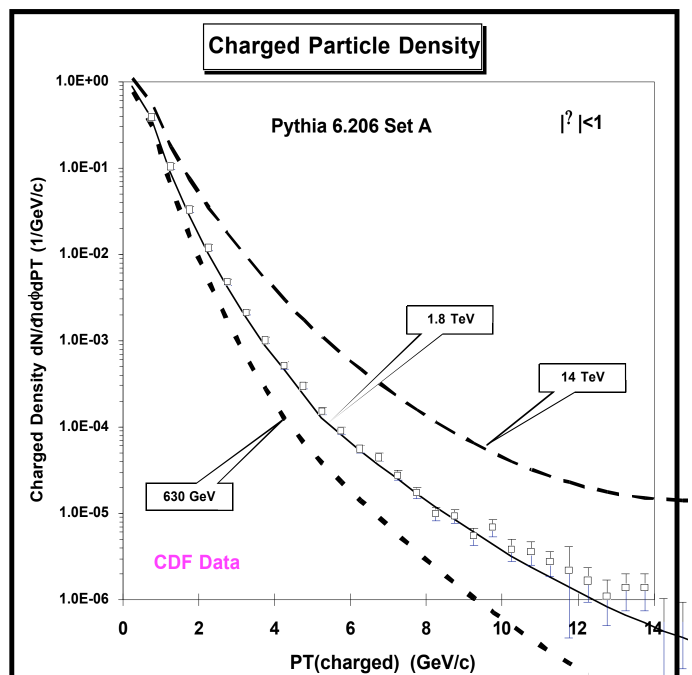
- Underlying event definition:
  – "beam-beam remnants": energy from interaction of spectator partons
  – "Initial state radiation": energy radiated off hard process before main interaction
  – Not wanted when e.g. measuring the top quark mass
- Can be estimated using Monte Carlo
  – Measurements led to tuning of MC generators: PYTHIA, Herwig+Jimmy

Measuring the Underlying Event

Leading Jet Direction



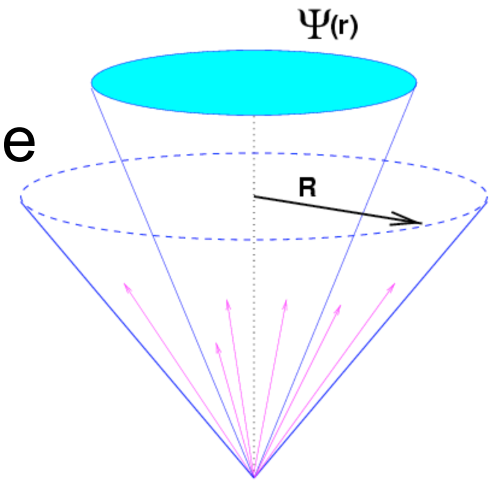




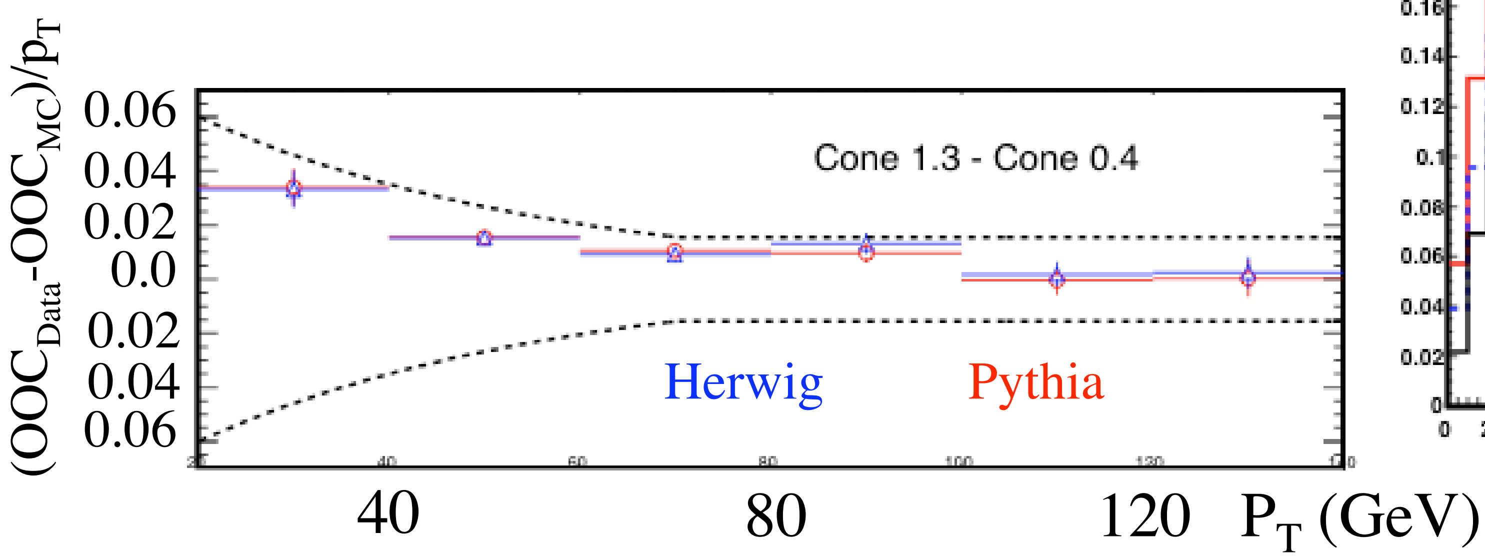
- Many studies exist about underlying event:
  - Checkout talks by Rick Field/U. of Florida
- At LHC we will need to measure it:
  - Expect it to be much harder than at Tevatron

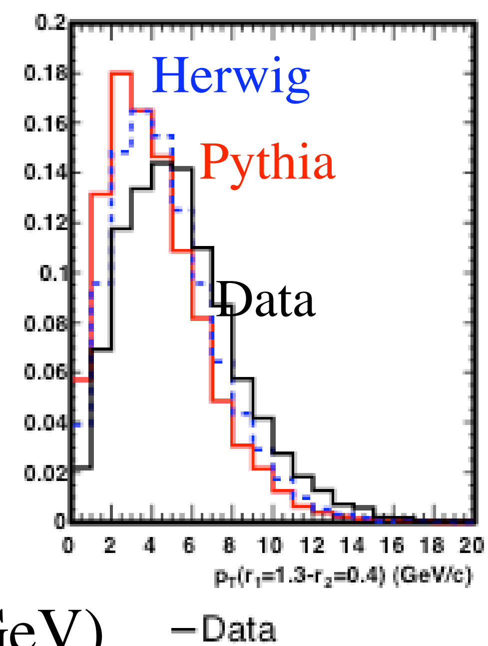
Out of Cone Energy (OOC)

- Out-of-Cone Energy:
  - Original parton energy that escapes the cone
    - E.g. due to gluon radiation
  - Jet shape in MC must describe data:
    - measure energy flow in annuli around jet

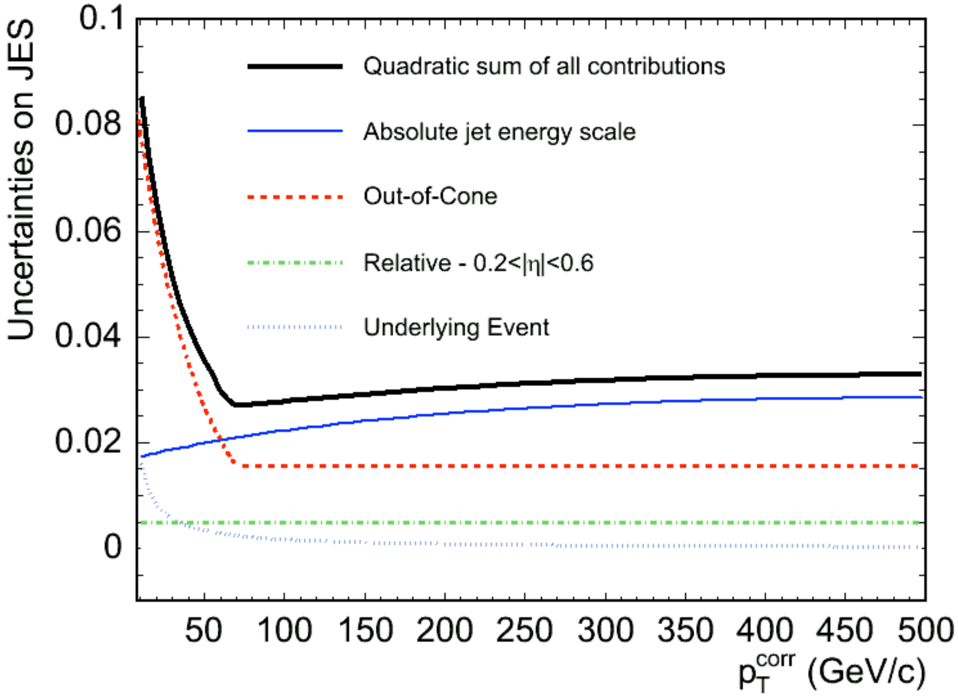


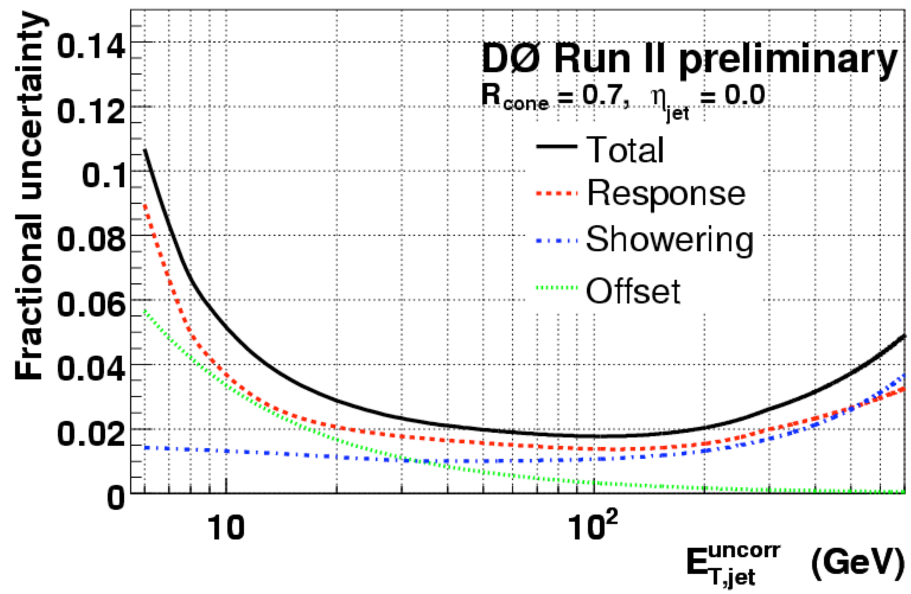
- Differences between data and MC
  - Lead to rather large systematic uncertainty





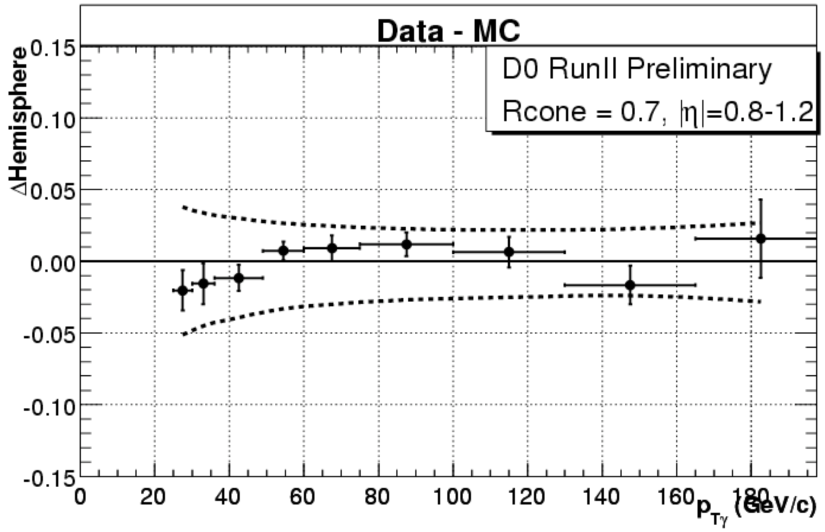
Jet Energy Scale Uncertainties

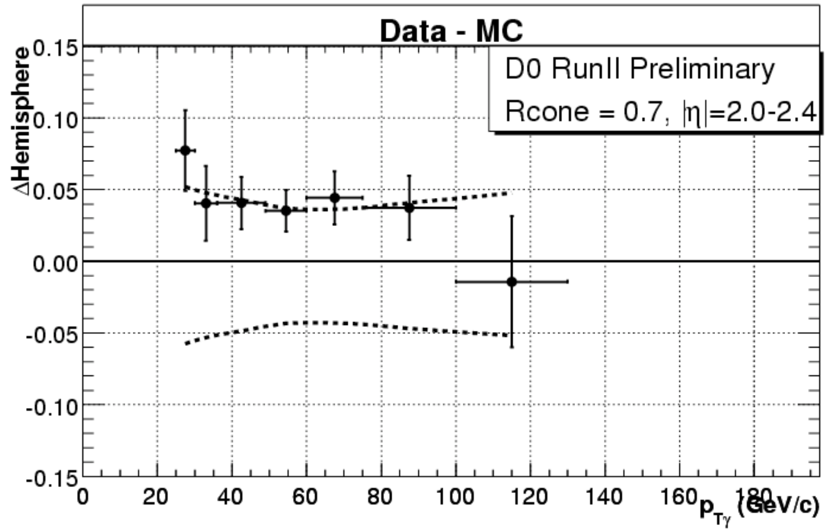




- CDF and DØ achieve similar uncertainties after following very different paths before
- Both collaborations have plans to improve further

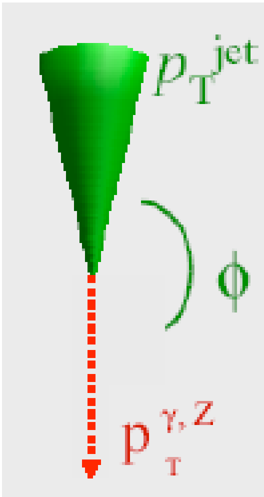
Compare data and MC after calibration

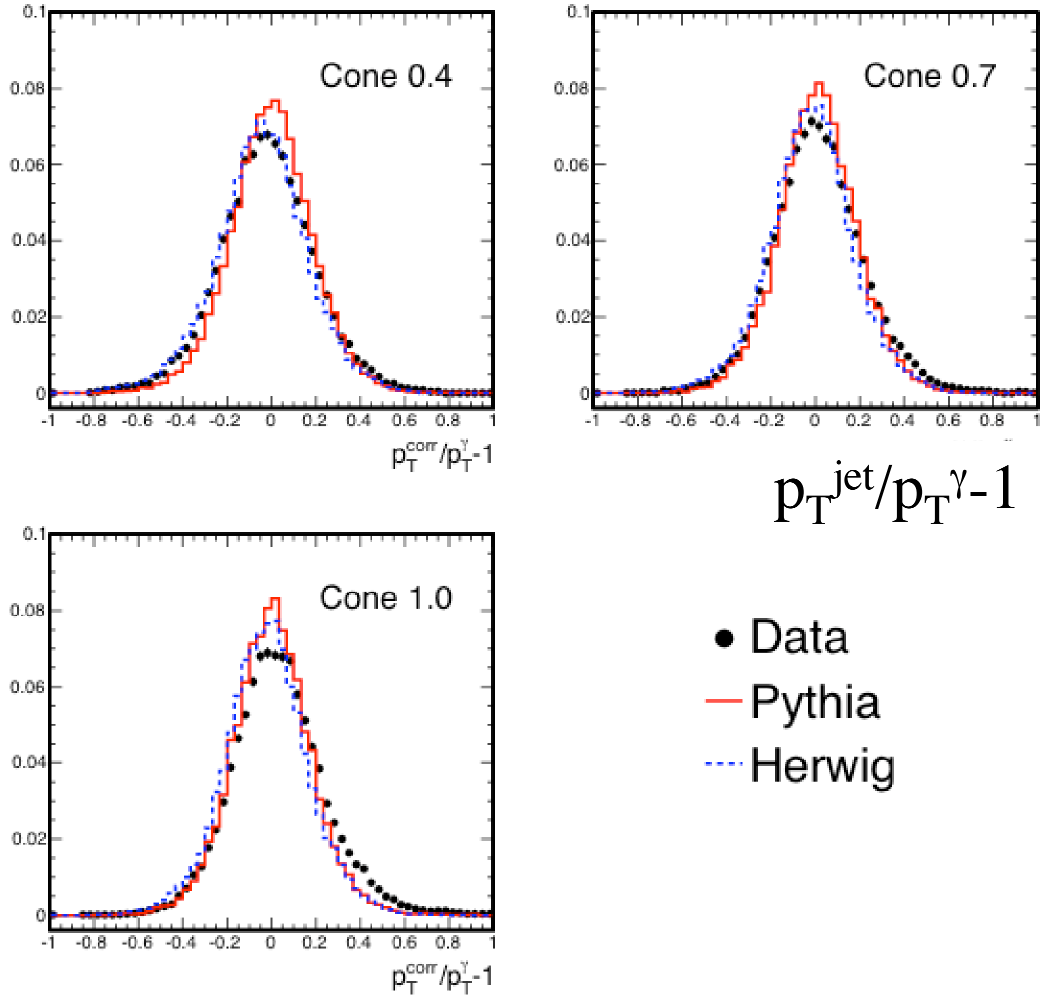




- Data and MC agree within systematic uncertainties

Photon-Jet P_T balance

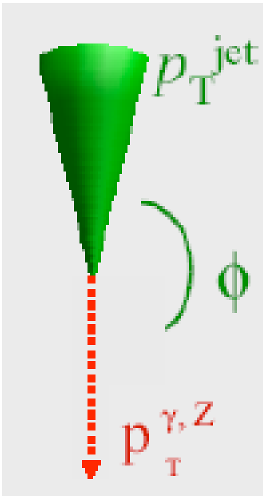


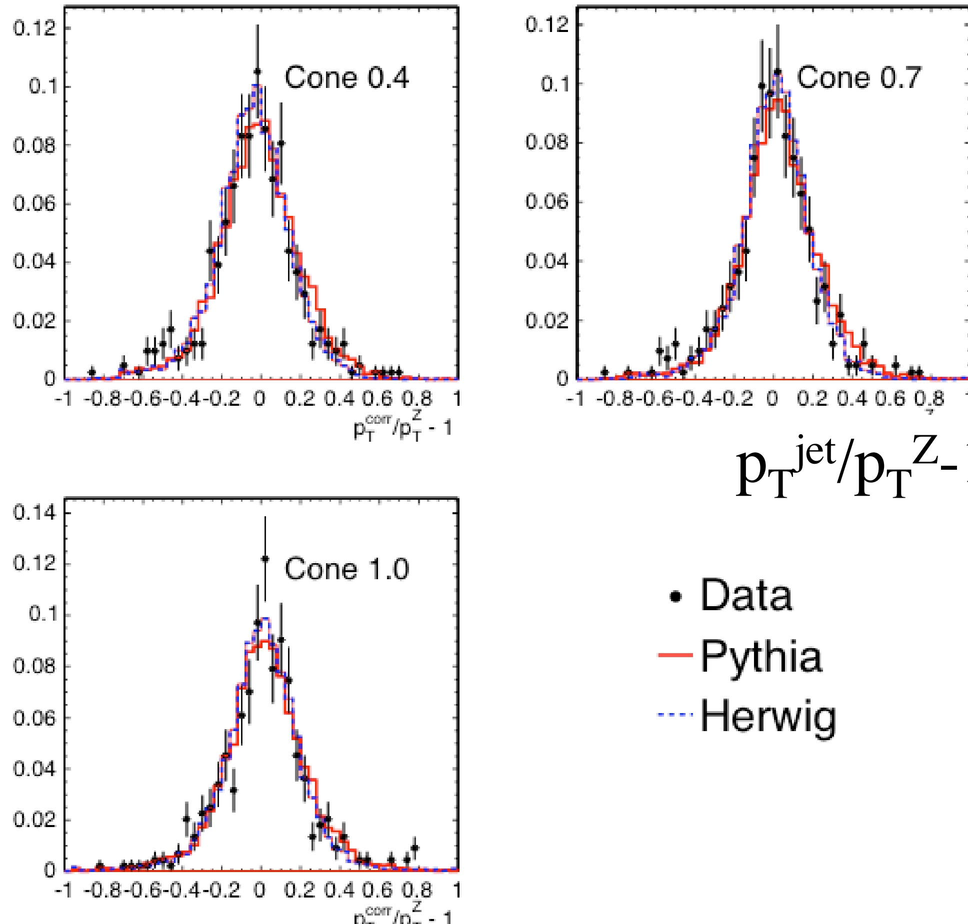


CDF

- Agreement within 3% but differences in distributions
  - Data, Pythia and Herwig all a little different
- These are physics effects!

Z-jet P_T balance





p_T^{jet}/p_T^Z-1

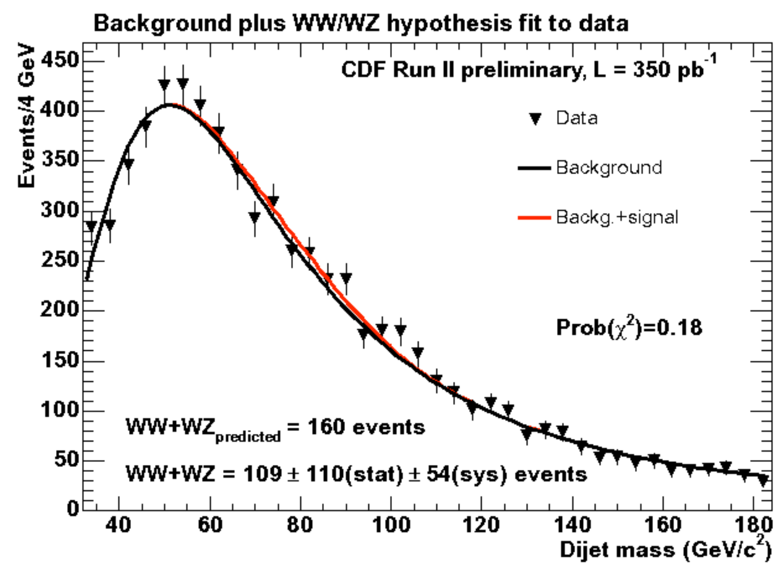
p_T^{jet}/p_T^Z-1

CDF

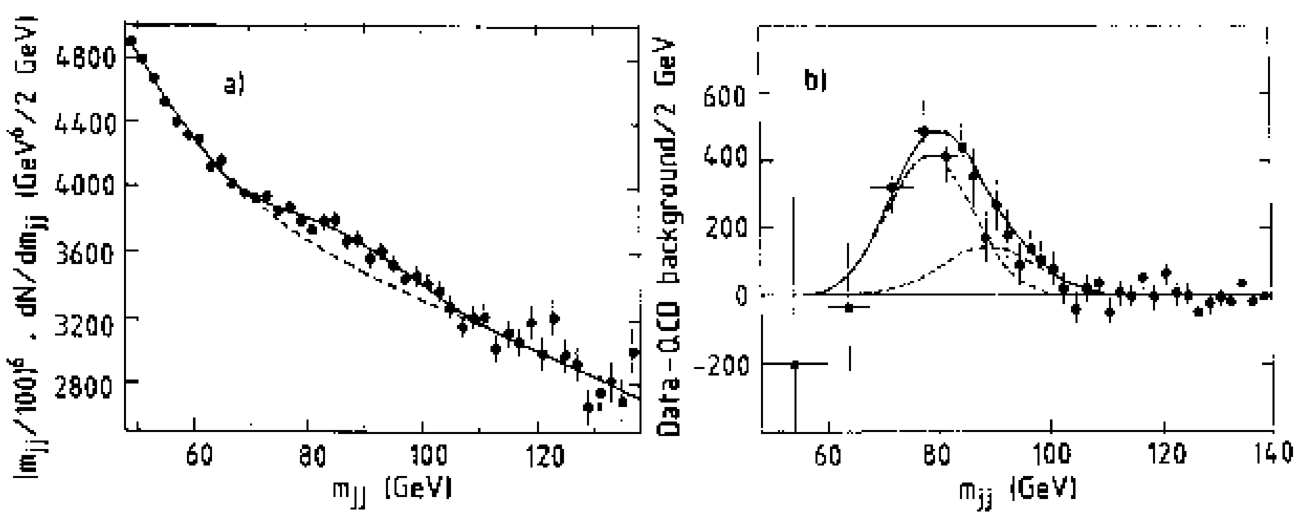
- Better agreement of data and MC than in photon-jet data
  - In progress of understanding this better together with Herwig and Pythia authors

Calibration Peaks from W's and Z's

- Very, very difficult to see inclusive decays of W's and Z's to jets
  - Small signal on huge background
    - W+2 jets
    - Photon+2 jets (UA2)
- Two best opportunities:
  - W in top quark decays
  - Z in bb decay mode

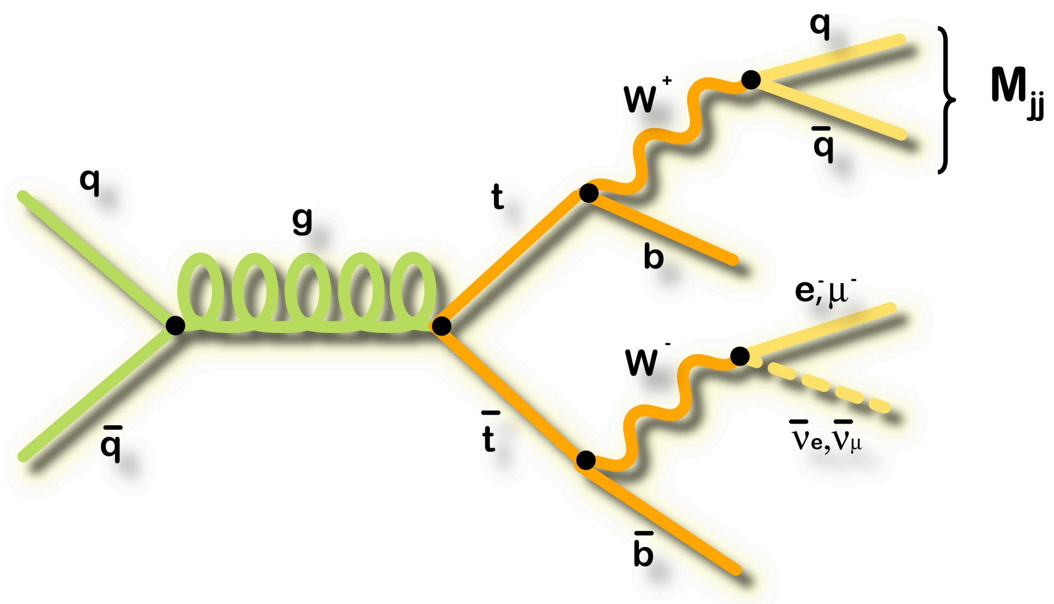


UA2, S/B ~ 1/35, ~5000 Signal



In-situ Measurement of JES

- Additionally, use $W \rightarrow jj$ mass resonance (M_{jj}) to measure the jet energy scale (JES) uncertainty



2D fit of the invariant mass of the non-b-jets and the top mass:

JES $\propto$ M(jj)- 80.4 GeV/c²

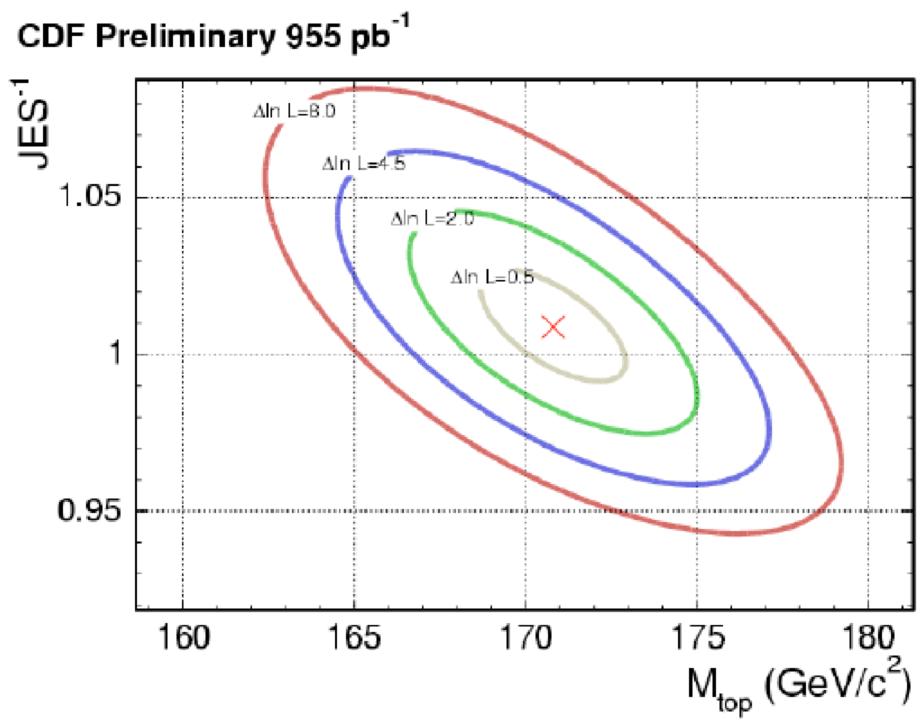
Measurement of JES scales directly with data statistics

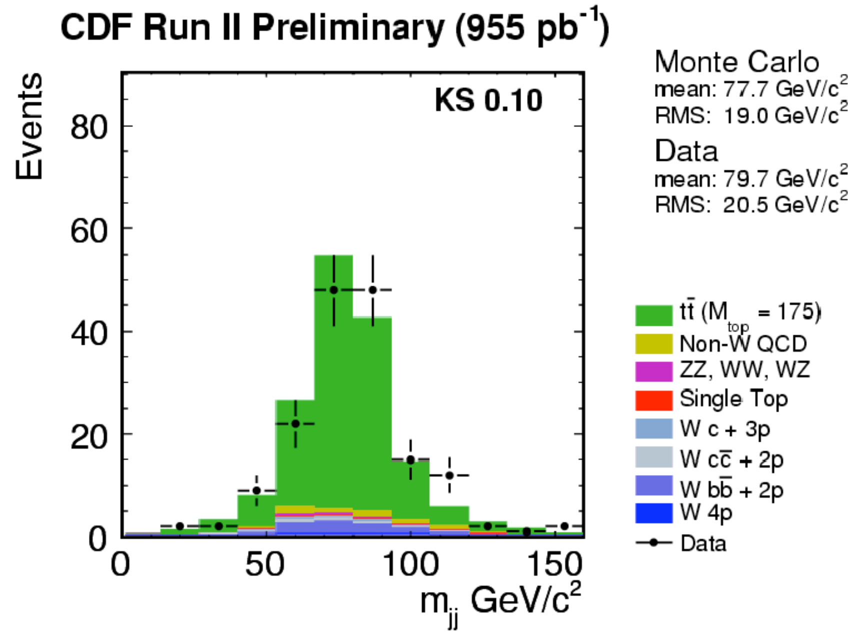
W→jj Calibration in Top Events

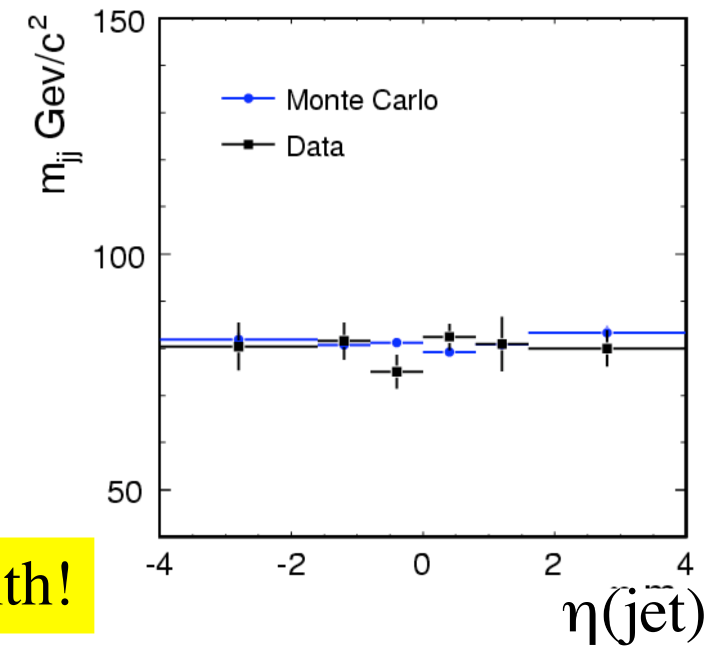
- Fit for ratio of JES in data to JES in MC

CDF (1 fb^{-1}): $\delta_{JES} = 0.99 \pm 0.02$
DØ (0.3 fb^{-1}): $\delta_{JES} = 0.99 \pm 0.03$

- Constrain JES to 2% using 166 events



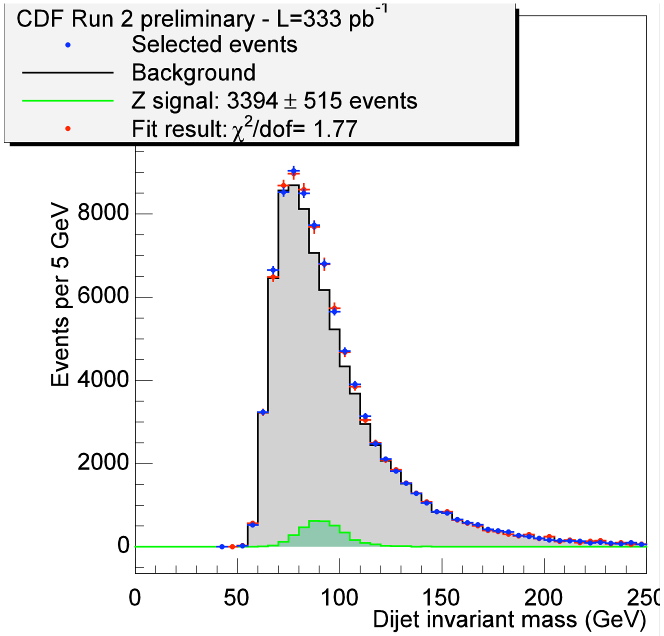


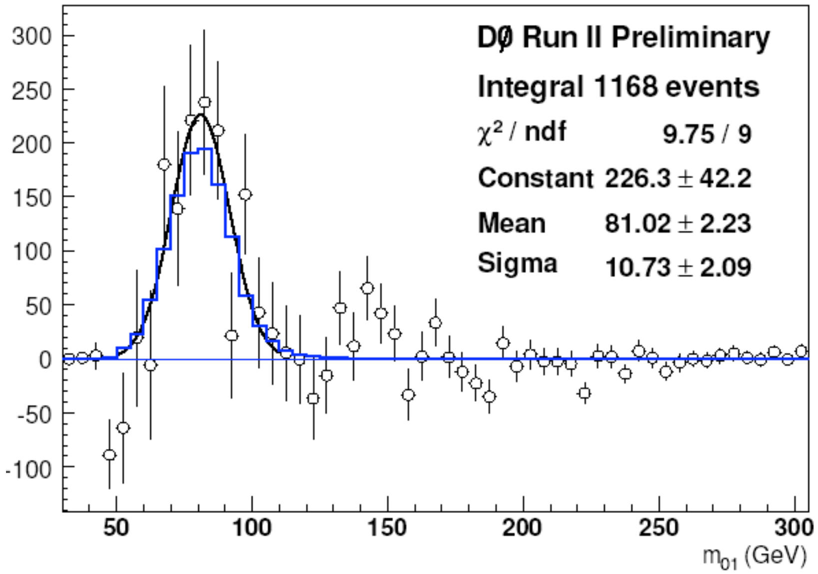


At LHC will have 45,000 top events/month!

Z->bb

- Z→bb decay mode:
  - Suppresses QCD background more than signal
  - Difficult to trigger
    - CDF uses secondary vertex trigger
    - D0 uses semi-leptonic decays collected by muon trigger
- Use this to measure difference between data and MC JES, e.g. DØ:
  - Data:
    - μ=81.0 +/- 2.2
    - σ=10.7 +/- 2.1
  - MC:
    - μ=83.3
    - σ=13.0





Conclusions

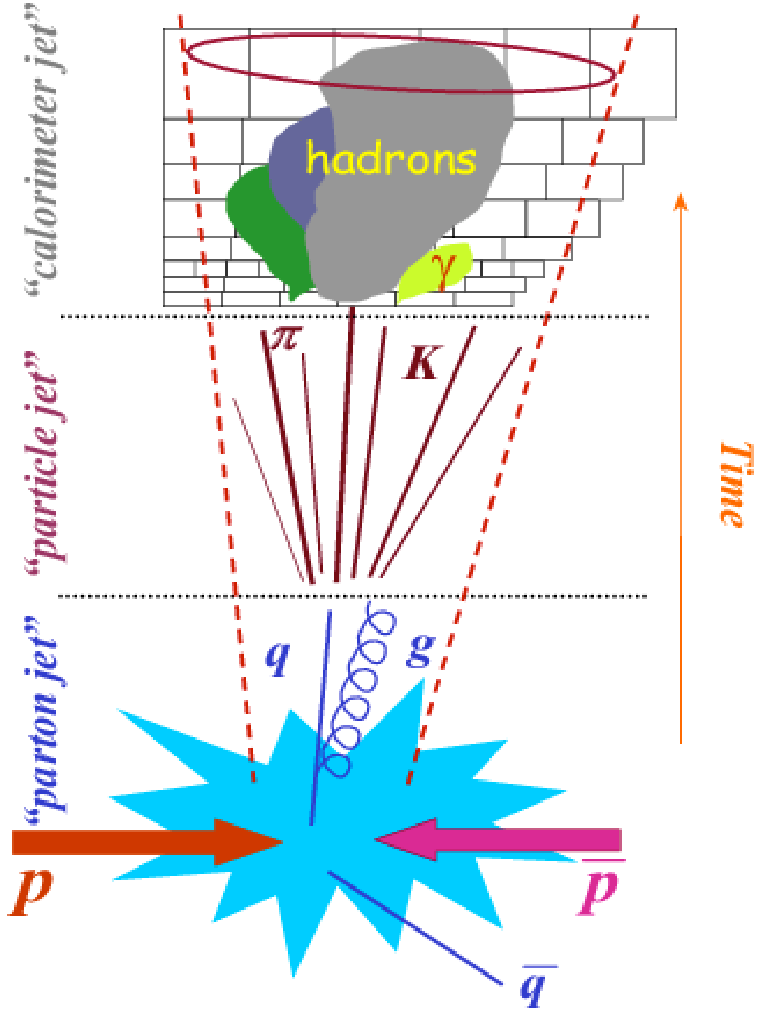
- Different calorimeters/collaborations can choose very different procedures:
  - CDF tunes simulation and then derives everything from MC
    - Systematic uncertainties depend on how well MC models data
  - DØ does a purely data based estimate
    - Systematic uncertainties depend on understanding of calibration process and sample composition
- Calibration signals:
  - MIP peak, E/p, $Z \rightarrow ee$ and Minimum Bias for calorimeter calibration
  - Di-jet balancing for relative response in cracks and in plug calorimeter
  - Isolated tracks for understanding calorimeter response to π′s
    - fragmentation needs to be modeled well
  - Photon-jet balancing for relative and absolute response
- Independent channels used for cross checks/systematic error:
  - Photon-Jet and Z-jet balancing
  - $Z \rightarrow bb$ peak and $W \rightarrow jj$ peak in top events
- 3-4% systematic uncertainty achieved so far
  - Better for jets in top events (~2%)

Jets are very complex and rather tough to calibrate

Backup

Jet Energy Scale

- Jet energy scale
  - Determine the energy of the partons produced in the hard scattering process
  - Instrumental effects:
    - Non-linearity of calorimeter
    - Response to hadrons
    - Poorly instrumented regions
  - Physics effects:
    - Initial and final state radiation
    - Underlying event
    - Hadronization
    - Flavor of parton
- Test each in data and MC



$$P_{T,jet}^{particle} = \left[P_{T,jet}^{measured} \times f_{rel} - MI \right] \times f_{abs}, \qquad P_T^{parton} = P_{T,jet}^{particle} - UE + OOC$$

Offset correction in D0

- Offset includes:
  - Underlying event
  - Multiple interactions:
    - # of Interactions ~ # of z-vertices
  - Noise
  - Pile-up from previous interaction
    - Due to long shaping time of preamplifier
  - Measure
    - Minimum bias events per tower
    - Depending on number of vertices